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ST___NG EFFECT OF NUCLEAR EXPLOSION

By

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UNEDITED ROUGH DRAFT TRANSLATION

SEISMIC EFFECT OF NUCLEAR EXPLOSION

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FROM THE PUBLISHERS

The book "The Damaging Effect of Nuclear Explosions" is based on material published in the foreign press. It gives a description of the striking power of nuclear weapons. The authors acquaint readers with methods of protection against nuclear weapons. The book contains a detailed and comprehensible explanation of the physical bases of atomic and thermonuclear munitions and considers the various damaging factors and simplest methods of calculating the area of the contaminated zone.

The principal matter contained in the book is intended for an extensive circle of readers - servicemen in the Soviet army and navy and also members of the DOSAAF (Voluntary Armed *Forces* Organization) acquainted with the fundamentals of physics and mathematics. A small section of the book may interest military and signal specialists who have received greater training in the field. When reading the book the less specialized reader may leave aside the complex problems without fear of not understanding the book as a whole.

TABLE OF CONTENTS

INTRODUCTION

Nuclear weapons, as is well known, have appeared comparatively recently and have been developed almost/without *ENTIRELY* use in military operations. Two atomic bombs were dropped by US aircraft in 1945 on the defenseless Japanese cities of Hiroshima and Nagasaki when Japan was already defeated and World War II was virtually at an end. In using the atomic weapons, the Government and military command of the United States pursued not so much military as political aims intended to demonstrate the power of the new weapon and to base their notorious policy of strength on it. The policy was based on the conviction held by the reactionary circles of the capitalist world that the USA would have the monopoly of atomic weapons for some time to come. But Soviet scientists and engineers were very soon able to liquidate the United State's monopoly. Atomic weapons were subsequently produced in Britain as well, and France is producing her own atomic weapons at the present time.

Thus, nuclear weapons are being rapidly developed and are becoming an integral part of armaments, determining the overall nature of modern warfare.

Nuclear weapons are weapons of mass destruction. This means that when a nuclear charge is exploded, the destruction covers a wide area containing, as a rule, a large number of destructible objects (people, buildings, ships, tanks, cars and so forth).

A nuclear charge contained in a bomb, in the warhead of a long-range rocket or used in some other form can replace hundreds, thousands or even tens of thousands of conventional bombs, rockets, etc. Present-day high-speed aircraft, guided missiles and long-range rockets make it possible to strike deep into the heart of enemy territory and from one to several dozen nuclear charge could be used, in accordance with the military plans.

These features of nuclear weapons have introduced fundamental changes in the methods of armed combat. It can be said that there has never been such a sudden leap forward in the development of means of warfare.

-1-

There is a marked variety of present-day atomic weapons. Their power is usually assessed on the basis of the energy released at the moment of explosion. The energy is measured in terms of TNT equivalent, that is to say, the amount of conventional explosive - TNT - which would produce the same amount of energy when exploded.

The TNT equivalents of nuclear charges described in the foreign press range from thousands to several million tons. On account of this, nuclear weapons can be used for tactical operations as well as for strategic purposes.

Nuclear weapons can be used both on land and at sea. There have been frequent mention in the foreign press of the possibility of nuclear explosions on the moon.

Nuclear charges can be contained in artillery shells of medium and large caliber, AS WELL AS/bombs; they can be used as warheads for rockets of different ranges, torpedos and various guided missiles.

The rapid development of nuclear engineering and the atomic industry has made it possible to produce a large quantity of nuclear explosive. According to the foreign press, the cost of one ton of TNT equivalent of thermonuclear fuel is not greater than one cent. HoweveR, the price is only a superficial indication of the production potentiality and cannot be used to describe the conditions for use of nuclear weapons in a large-scale armed conflict.

A highly important feature of nuclear weapons is the fact that they produce radioactive products when they explode. These products may spread through the earth's atmosphere under certain circumstances, causing/to HUMAN and animals all over the globe. The danger is excessive when there are large-scale nuclear explosions close to the earth's surface, when the radioactive products settle on dust particles and are carried for hundreds of kilometers by the wind in the form of a concentrated stream.

Nuclear explosions are a threat to the health and survival of mankind. Their effect on the health of children is particularly great. It follows from this that not only the use of nuclear weapons during wartime, but the testing of them

AS WELL
/is a threat to the whole of mankind.

Recognizing the danger of these weapons, the Soviet people, led by the Communist Party and Government, together with the working people of the whole world is engaged in a consistent and stubborn campaign for the banning of all nuclear tests, the production of nuclear weapons and preparations for their use in war, and also against the arms race.

In his speech at the United Nations General Assembly on September 18, 1959, N. S. Khrushchev said that never before in the history of man has the arms race been conducted at such a rate or been frought with so much danger as today, in the era of the atom, the electron and the conquest of space.

No too long ago rapid-firing automatic weapons, tanks, long-range artillery and bombs were considered the most powerful means of extermination. But can they really be compared with the atomic weapons which are available at present? We have now reached a stage at which it becomes difficult to think of a more powerful weapon than the hydrogen bomb, which is virtually infinite in its power. Even if we collected together all the means of destruction which man has/*EVER* possessed in the past, in power they would only be a fraction of what the two or three great powers possessing nuclear weapons have at their disposal today.

A tremendous amount of destructive energy is released during the explosion of one, mark you one, large hydrogen bomb. The press has quoted an American expert on nuclear physics, W. Davidson, who points out that the explosion of one hydrogen bomb releases more energy than all the explosions carried out by all countries in all the wars tha' mankind has known. He is probably right. And *DARE* we really forget that the destructive power of military weapons attain such collossal proportions? And *DARE* we forget that there is now no place on the globe which is inpregnable to nuclear rockets?

It is difficult to imagine the aftermath which would be caused by a war in which these monstrous methods of annihilation were used. If A/ *WAR* is allowed to break out, the *DESTRUCTION* would be counted not in millions, but in many tens or even hundreds of millions of human lives. It would be a war without any distinction

-3-

between front and rear, between children and soldiers. It would raze to the ground many major cities and industrial centers, it would lead to the everlasting destruction of the greatest cultural achievements which took the human genius centuries to achieve. Nor would such a war spare the future generations. Its poisonous trail in the form of radioactive contamination would cripple people for a long time to come and result in the loss of many lives.

Hence the importance of the study of nuclear weapons and their effects is far beyond the limits of specialized warfare.

This book only considers explosive nuclear weapons, their working principle and combat characteristics. Before going on to more detailed examination of these weapons, we should make the following comments. At the present time such terms as nuclear, thermonuclear, hydrogen weapons, cobalt bombs, and so forth commonly used for the new weapons.

The term "nuclear weapons" means that we are discussing weapons based on the use of energy released by the conversion of atomic nuclei. The term is therefore of a very general, generic importance. Thermonuclear weapons are those based on thermonuclear reactions, that is to say reactions involving the combination of light atomic nuclei at very high temperatures. The hydrogen bomb is based on thermonuclear reaction, in which heavy hydrogen -- deuterium and superheavy hydrogen -- tritium, take part. It is conventional to use the term atomic weapons to describe weapons containing basically such atomic explosives as uranium 233, uranium 235 and plutonium. But in recent time, to judge from the material contained in the foreign press, the main type of new weapon is one in which there are various nuclear reactions in different ratios during the explosion.

Hence it can be considered that the term "nuclear weapons" is extended to cover all types of weapons in which the explosion is caused by nuclear reaction.

In this book we use the term "nuclear bomb" and "nuclear weapons", irrespective of the type of reaction RELEASING the explosion energy. Whenever necessary, the type of bomb, WHETHER based on fusion or fission, will be indicated separately.

-4-

As is well known, nuclear weapons are only one of the PRODUCTS of nuclear engineering, developing so rapidly at the present time and of possible use in warfare. X

No matter how varied the methods of using atomic energy in war, nuclear weapons are undoubtedly the most important aspect OF IT at the present time. Their effect on the nature of modern warfare is extremely great and varied, and they must be studied in order to understand correctly both the warfare itself, as well as present-day international economics and politics.

The success gained by the USSR in developing atomic weapons has been possible through the Communist Party's consistent policy aimed at a rapid and multilateral development of the whole industry, in particular, metallurgy, machine-building, instrument-building, electronics and chemistry. It is on this account that the Soviet Union at the present time is batch producing nuclear-rocket missiles of all types and purposes and other defense measures suited to the present level, enabling the valiant Soviet armed forces to defend our great country; and if necessary to retaliate against any agressors or adventurers.

The advancement made by the USSR in the development of nuclear weapons is further, obvious proof of the undoubted advantage of the socialist system, the tremendous development of Soviet science and the high technical level of the whole of our industry.

In his speech at a Soviet press conference in the Kremlin on November 14, 1959, N. S. Krushchev said that "we now have such a large number of rockets and such a number of atomic and hydrogen warheads that if we are attacked, we can wipe all POTENTIAL enemies from the face of the earth". Krushchev went on to point out that while visiting a certain plant he had been shown the way the workers, engineers and scientists were building rockets. "When you look at this KIND OF production, you experience conflicting feelings; the plant is producing the most deadly, most destructive weapons, while at the same time you are proud that you have them... In one year the plant which we visited has made 250 rockets with hydrogen warheads on an assembly line. This means many millions of tons if you think in terms of

-5-

ordinary explosives. You can understand that if weapons of this kind are exploded over a country, nothing would be left."

"Those are the powerful weapons which we have available to defend our country. While possessing them, we declare that we are ready to drop them all in the sea in the interests of peace on earth, in the interests of the future, so that everybody of the present and future generation can live in peace, so that they know that we do not only not want war, but we do not even want to have the means of waging it. We are ready to destroy all these weapons immediately, if other countries follow our example"*.

In his report at the Session of the USSR Supreme Soviet on January 14, 1960, Krushchev said that "The Soviet army now has armaments and a fire power never possessed before by any army. I stress once again that we have so many nuclear weapons – atomic and nuclear weapons – and the appropriate rockets to carry them to the territory of a potential agressor, that if any madman causes an attack on our State or any other socialist State, we can literally wipe the country or countries attacking us from the face of the earth."

Every sane person fully realizes that atomic and hydrogen weapons create the greatest threat to countries with the densest population. Naturally, in the event of a new world war, all countries would suffer to some extent. We would also suffer great disaster, and would lose many lives, but we would live through it, for our territory is vast and the population is not concentrated in major industial centers to the same extent as in other countries. The West would suffer incomparably more. If the agressors unleash a new war, it will not only be their

*
N. S. Krushchev. The Soviet press must be the strongest and the most militant! Speech at Soviet press conference in Kremlin on November, 14, 1959. "Pravda" of November 18, 1959.

-6-

last one, it will be the end of capitalism since the peoples will fully realize that capitalism is the source of war, and they will no longer tolerate a regime which brings suffering and disaster to mankind.

"...Soviet citizens may rest assured that the present armaments of the Soviet army will fully ensure the impregnability of our country"*.

*
N. S. Krushchev. Armament/the only way to strengthen peace and ensure friendship among peoples. Report given at session of USSR Supreme Soviet "Pravda" of January 15, 1960.

CHAPTER I

BRIEF DESCRIPTION OF WORKING PRINCIPLE OF NUCLEAR WEAPONS

Working Principle of Nuclear Weapons

1. The structure of the atom and its nucleus

In order to understand the effect of an atomic explosion, we have to know how the nuclear energy is released. To do this we must find out how matter is constructed as a whole, and whereabouts the energy in it is stored.

In our everyday lives we come into contact with different materials and objects surrounding us. These objects possess characteristic properties: size, shape, color, smell, weight and so forth. The properties of matter may change. We know that matter can expand and contract, can change from the solid state to the liquid or gaseous state, can sometimes be luminous, and so on.

How can all this be explained? All matter consists of extremely fine particles, invisible to the naked eye, which are known as atoms. The atoms of different substances have different structures. For example, a hydrogen atom is different from an iron atom, and an iron atom is different from a uranium atom. Substances consisting of homogeneous atoms are known as chemicaly simple substances, or chemical elements. At the present time we know of 102 chemical elements. They are all represetnted in Mendeleyev's periodic system.

There is a huge variety of matter in nature. At the present time there are reckoned to be more than a million types. Where have they come from?

Single atoms form new particles - molecules - by combining together. In turn the combination of molecules leads to the formation of compounds (water, oil and so on). Compounds can be split up into elements by physical or chemical methods.

If we decompose a compound such as water into its component parts, we see that the molecule of water consists of two atoms of the chemical element hydrogen and one atom of oxygen. A molecule of cooking salt consists of a sodium atom and a chlorine atom.

The number of atoms making up molecules of more complex substances is counted in dozens and sometimes hundreds or more.

Steel, concrete, wood and soil also consist of various molecules. They are all compounds - as distinct from, say, hydrogen, oxygen, iron, silver, uranium and so on, which are elements. Molecules differ both in composition as well as size. Under normal circumstances (0 C and normal pressure) a cubic millimeter of air contains $2,687 \cdot 10^{16}$ molecules. At the present time Soviet scientists have constructed an electron-ion projector, by means of which we can see simple and compound molecules.

Thus, all matter in nature, both elements and compounds, consist of atoms.

Atoms are, so to say, the bricks with which the whole of nature around us, and we ourselves, are made. They are the smallest particles into which matter can decompose during chemical reactions.

It was thought for a long time that the atom was INDIVISIBLE. Even the word itself is a translation of the Greek word for 'indivisible'. But the advancement of science has shown that the atom is a compound particle. Although atoms are extremely small and cannot be seen through the most powerful microscope, they differ from each other in structure, size and weight.

An atom consists of a positively charged nucleus, around which negatively charged particles, called electrons, rotate; these electrons form the electron shell (Fig. 1).

The electron is a tiny particle of matter possessing a negative charge. No charge smaller than that possessed by the electron has ever been observed. Hence in atomic physics it is customary to measure all charges in electron charges.

The nucleus consists of protons and neutrons, which are together termed nucleons. The size of the atom is determined by its electron shell and amounts to the order of 10^{-8} cm. The size of the nucleus, however, is of the order of $10^{-12} - 10^{-13}$ cm. If we imagine the atom to be a sphere 100 mm in diameter, the nucleus inside can be imagined as a pellet with a diameter of about 1 mm.

The proton is a positively charged particle, equal in absolute value to the electron charge. The mass of the proton is 1836 times greater than that of the electron.

Neutron. This is a nuclear particle which does not have an electric charge. The mass of the neutron is approximately equal to that of the proton.
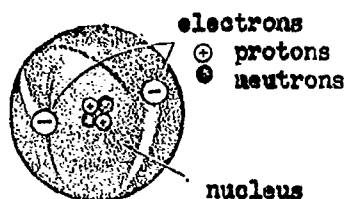
Fig. 1. Diagramatic structure of helium atom.

Atomic nuclei of different elements possess a different number of protons, ranging from one (hydrogen atc) to 102 (nobelium atom), and therefore different charges as well.

The number of protons determines the property of the atom of a chemical element and is equal to the ordinal (atomic) number Z of the element in the periodic table. For example, a hydrogen atom has one proton, hence hydrogen heads the list, the helium atom has two protons and therefore comes second, and so forth.

The number of electrons in the shell of the atom is usually equal to the number of positive charges (protons) in the nucleus. On account of this the atom as a whole is electrically neutral under normal conditions, i.e., it possesses no charge. The equality of the number of protons and electrons in the atom suggests that almost the entire mass of it is contained within the nucleus, since the proton (neutron) is 1836 times heavier than the electron. We know that energy is directly proportional to mass. It follows from this that almost all the energy of an atom is contained within the nucleus as well.

Another important characteristic of the atom is its mass number A. The mass number is equal to the number of protons and neutrons (nucleons) in the nucleus and is

numerically equal to the atomic weight, rounded off to a whole number. By knowing the mass number of the nucleus A and the number of protons (charge) Z, we can easily determine the number of neutrons N as the difference between A and Z: N = A — Z. For example, helium has the most number A = 4, so the charge Z = 2. The number of protons in its nucleus is then N = 4 — 2 = 2. These two numbers Z and A are usually placed beside the symbol for the chemical element; Z is a subscript on the left and A is a superscript on the right. The symbol then looks as follows: for helium $_2\text{He}^4$, for iron $_{26}\text{Fe}^{56}$, and so on. The number of protons in the given nucleus remains unchanged. But the number of the neutrons may vary. Atoms whose nuclei contain the same number of protons, though a different number of neutrons have identical chemical properties, but different atomic weights (mass numbers). These atoms are called isotopes. Practically every chemical element has isotopes. Hydrogen, for instance, has three. Besides the commonest hydrogen isotope $_1\text{H}^1$, there are two others known: heavy hydrogen $_1\text{H}^2$ (deuterium, D) and super-heavy hydrogen (tritium, T). They both have one proton in the nucleus (one electron each on the shell), but deuterium has an extra neutron and tritium has two extra neutrons.

Uranium has eleven isotopes, but only three are found in natural compounds of uranium: Uranium 238 (mass number A = 238), uranium 235 and uranium 234). Their nuclei contain 92 protons each and 146, 143 and 142 neutrons, respectively.

At the present time the 102 chemical elements possess more than 1000 known isotopes.

Structure of the electron shell. As has already been pointed out, the electrons orbit the nucleus in an area which has been given the name of the electron shell. In it each electron moves in a definite orbit.

The electron orbits are different distances from the nucleus and are grouped into layers surrounding the latter. Each layer contains no more than a set number of electrons. The closest layer to the nucleus, known as the K shell, contains only two electrons, the next layer, the L shell, contains not more than 8, the

-11-

third, M shell contains not more than 18 electrons and so on. Fig. 2 shows the schematic structure of electron shells in certain chemical elements.

Attraction is exerted between the electrons and the nucleus of the atom. Hence the electrons while moving about keep in strictly defined orbits in the same way as planets moving round the sun. The closer the electron is to the nucleus, the greater its bond with the nucleus, and vice versa.

Consequently, it is always necessary to expend work in order to shift an electron from a lower to a higher orbit.
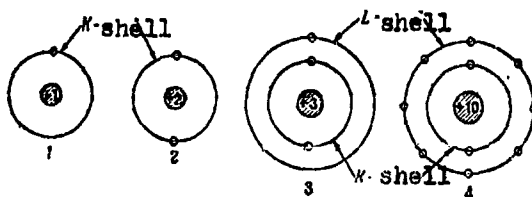
Fig. 2. Diagramatic structure of electron shells: 1) hydrogen; 2) helium; 3) lithium; 4) neon.

Each shell corresponds to a certain energy possessed by the electrons in that particular shell. The total energy of the electron in the atom is composed of the kinetic energy of its motion around the orbit and the potential energy of its attraction to the nucleus.

Under normal, stable conditions the electrons are situated on the closest orbits to the nucleus, which correspond to the lowest energy levels of the electron, and therefore/ of the atom as a whole.

As the distance from the nucleus increases, the kinetic energy of the electron is reduced while the potential energy is increased (in the same way that the potential energy of a stone is increased as it is raised above the GROUND

..   , and the less the kinetic energy, the greater the extent to which this

-12-

happens. Hence the total energy of an electron is also increased as the radius of the orbit is enlarged, and the energy of the atom as a whole is increased as well. The possible values of the internal energy of an atom has come to be called energy levels[1].

The hydrogen atom only has one electron, which is situated in one of the orbits of the first shell (K shell). The helium atom has two electrons situated in two orbits in the first shell. Thus, the first shell is completely filled in the case of helium.

Atoms whose shells are completely filled are chemically inactive; not only do they not combine with other atoms, they do not even form molecules with each other. Such atoms make up the so-called inert gases - helium, neon, argon and so on.

The brilliant Russian chemist, Mendeleyev, found that the properties of the chemical elements are periodically repeated at regular intervals. It turned out subsequently that these properties are a reflection of the regularities governing the structure of an atom and its electron shell.

In Mendeleyev's table, helium is followed by lithium with three electrons in the shell:- two in the first, while the third begins a new shell.

This electron is not as strongly bound to the nucleus as the first two, and a lithium atom, just as a hydrogen atom, gives it up very easily during chemical reactions. The next elements after lithium are beryllium, boron, carbon, and so on, and these preserve the K shell with two electrons, but the number of electrons in the second L shell increases successively by one unit, until it reaches eight in the neon atom. This means that the neon atom has two complete shells K and L, the first containing two and the second containing eight electrons. Here again we have

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[1] The term "energy level" is used by analogy with the energy spent on raising a body to a certain height. The higher the body is raised, the greater its potential energy. The difference between the potential energy of the body at two different heights is determined by the difference in levels.

a stable combination of electrons in the electron shell, on account of which neon, like helium, neither gives up nor accepts electrons. Neon is therefore classed as an inert gas. Neon is followed by sodium. Sodium has eleven electrons in its shell. Ten of them form the K and L shells, while the eleventh begins a new shell, M. Thus the sodium atom has a structure similar to lithium; they each have one electron in the uppermost shell, which makes them chemically allied. An electron may move round its orbit in stable fashion, but this does not mean that it is always "tied" to it. If some outside force is applied to it (collision with another electron, heating, and so on), the electron may "jump" from AN orbit close to the nucleus to one further away. Here its energy is increased, or, as it is usually . the "atom is excited". Atoms remain in the excited state for a very short time, after which the electron returns to its original orbit, close to the nucleus.

When the electron is transferred back to its original orbit, its energy is reduced, and the surplus is emitted in the form of electromagnetic radiation (called a photon). The amount of energy transferred by this photon is equal to the energy difference in the different electron shells (during excitation and prior to excitation).

If $\underline{E}_1$ is the energy of the electron prior to excitation and $\underline{E}_\lambda$ is its energy during excitation, the energy transferred by the photon is $\mathcal{E} = \underline{E}_\lambda - \underline{E}_1$.

What type of radiation is emitted when an atom changes from the excited state to its normal state? Depending on the energy of the photon, when an electron shifts from a more distant orbit to one closer to the nucleus, there may be either luminous or x-ray radiation.

The greater the energy of the photon, the shorter the wavelength of the radiation.

An outside force acting on an electron may be such that the electron is detached from the atom. Removal of electrons from the atomic shell is termed ionization. An atom may be ionized through detachment of one or more electrons

from it (in the latter case it is multiple ionization). An atom or molecule which has lost one or more electrons becomes a positive ion. The positive charge on this ion is equal in magnitude to the charge of the lost electrons. The energy required to remove an electron completely from an atom without imparting kinetic energy to it is termed the bond energy of an electron in an atom.

The greatest bond energy is possessed by electrons in the K shell. Electrons from more distant shells exhibit less bond energy (they are not bound to the nucleus so strongly). This is because, first, they are situated at a much greater distance from the nucleus, and, second, the attraction of the outside electrons by the positive charge is compensated to a great extent by repulsion by the negative electrons in the inside shell.

Measurements show that the energy required to detach one of the outside electrons from an atom ranges from 5 to 20 ev, according to the ordinal number of the atom. When this electron returns to its former orbit, a light quanta of energy of 5 - 20 ev is emitted as well. This energy corresponds to the wavelength of infra-red, visible and ultra-violet light. The return of the electron to a positive ion is termed recombination. Thus, the emission of infra-red, visible and ultra-violet light (in the optical region) involves the behavior of the outer-most electrons in the atoms.

In order to remove electrons from the inside shells of complex atoms we have to have much greater energy than to remove them from the outside shells. For instance, to remove an electron from the K shell in a sodium atom, we need energy of about 1100 ev, for copper more than 9000 ev, AND/for tungsten about 70,000 ev. The transition of electrons in this case from the L shell and subsequent shells to a free place in the K shell results in the emission of high-energy quanta corresponding to x-rays.

Let us now consider how the release of energy locked away in the atomic nucleus takes place.

2. Reactions involved in nuclear weapons

_15 _

Some of the energy contained within the electron shell is released during chemical reactions (combustion of fuel, explosion of conventional explosives, and so forth) and is called chemical energy. In the process there is rearrangement of the molecules, causing variations in the electron shells of the atoms, while the nuclei remain unchanged. Reactions may either involve *THE* release of energy or *the* absorption of it.

When 1 kg of TNT is exploded, about 1000 kilocalories are released, up to 7000 kilocalories are released when 1 kg of good coal is burnt, and up to 11,000 kilocalories of chemical energy are released when 1 kg of oil is burnt. Far greater amounts of energy may be obtained from atomic nuclei since the energy reserved in them is many times greater than . in the electron shells. The energy released during nuclear reactions is millions of times greater than that released when we burn the same amount of the best grade fuel.

As distinct from chemical reactions, nuclear reactions involve changes in the atomic nuclei. Here there is an increase or reduction in the number of neutrons or protons, leading to the formation of a new chemical element or a new isotope of the original element.

During nuclear reactions, just as in chemical reactions, there is either emission or absorptions of energy.

The energy which is reduced or absorbed is conventionally called nuclear energy.

In order to explain nuclear reactions involved in nuclear weapons, we must first consider the forces acting between the particles (protons and neutrons) in the nucleus.

As is well known, particles with charges of the same sign repel each other. It might seem that under such circumstances the atomic nuclei which is made up of like charged particles - protons - ought to decay spontaneously into component parts, that is to say protons and neutrons. In most cases, however, nuclei are very stable. This is due to the fact that apart from the electrostatic repulsion

-16-

forces, in the nucleus there are special nuclear forces at work, preventing its destruction.

Nuclear forces are only manifested at close distances; their range does not exceed 10^{-12} cm. Outwardly nuclear forces are similar to molecular cohesion forces in a fluid and make the nucleus spherical, which is one of the most stable of the known shapes.

The attraction forces (nuclear forces) in nuclei in most of the atoms encountered in nature predominate over the electric repulsion forces, hence they are very stable. The stability of the nucleus is a function of the ratio of protons to neutrons in it. If the number of protons and neutrons deviate from a set ratio, the nucleus is unstable. Unstable nuclei change spontaneously, turning into stable ones. In nature this phenomenon is observed in the nuclei of heavy elements - uranium, radium and certain other ones. In them the forces of repulsion sometimes exceed the nuclear forces of cohesion and split up the nucleus into pieces. But this spontaneous fission is very rare.

Since the protons and neutrons in the nucleus are attracted to each other, in order to split the nucleus into its component particles, we obviously have to work against the nuclear forces and therefore spend some energy. Conversely, when forming nuclei from protons and neutrons, the equivalent amount of energy is released. The energy released during the formation of atomic nucleus from protons and neutrons is termed the binding energy.

How can we determine the binding energy of the nucleus of a chemical element?

It has been experimentally established that the mass of the nucleus of any atom is always smaller by a slight value Δm than the sum of the masses of the individual neutrons and protons required to form it. Let us show this from the example of the helium nucleus $_2He^4$, which comprises two protons and two neutrons. The sum of the masses of the two protons and two neutrons is 2 x 1.0076 + 2 x 1.0089 = 4.033 atomic units of mass (aum)[1]. But the mass of the helium nucleus is equal to 4.003 aum. Consequently, when the helium nucleus is formed, the loss of mass is

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[1] 1 aum = $1.66 \cdot 10^{-24}$ g.

-17-

0.03 aum. The drop in mass during the formation of nuclei has come to be called the mass defect.

The corresponding amount of energy released can easily be determined from the released mass on the basis of the law of the interrelation between mass and energy. When determining the energy from the formula given below for mass in terms of atomic units of mass, we have to convert into grams. The formation energy for a helium nucleus is equal to $E = \Delta mc^2 = 0.03 \cdot 1.66 \cdot 10^{-24} \cdot (3 \cdot 10^{10})^2$

$$= 45 \cdot 10^{-6} \text{ эрг} = 1.08 \cdot 10^{-12} \text{ cal.}$$

here $\Delta \underline{m}$ is the mass in grams;

$\underline{c}$ is the speed of light in cm/sec.

In order to determine how much energy is released in the formation of one gram of helium, we multiply the amount of energy derived by the number of atoms in a gram of helium[1], which is 1.5   10 . The energy released during the formation of 1 gram of helium atoms is 1.08   10   x 1.5   10   = 1.6   10   cal. This is roughly the same amount of energy produced by the Dneproges Power Station in an hour.

In terms of megaelectron volts the binding energy of the helium nucleus is

$$\frac{1.08 \cdot 10^{-12}}{3.8 \cdot 10^{-20}} = 28 \cdot 10^6 \text{ эв} = 28 \text{ Mev}$$

It is sometimes easier to use the specific binding energy per 1 nucleon E/A, for the calculations, rather than the total binding energy for the whole of the nucleus E. Consequently, for a helium nucleus consisting of four nucleons (A = 4), the binding energy per nucleon is E/A = 28/4 = 7 mev. The mass defect is determined for all nuclei of chemical elements. For example, in the case of the heavy hydrogen (deuterium) nucleus, it is 0.00235 aum, for the lithium nucleus 0.034 aum, nickel nucleus, 0.171 aum, krypton nucleus, 0.756 aum, and uranium

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[1] In atomic physics the unit of energy is conventionally the electron volt (ev). The electron volt represents the kinetic energy which is acquired by an electron when it passes through an accellerating electric field with a potential of 1 volt.

$1 \text{ ev} = 1.6 \cdot 10^{-12} \text{ erg} = 3.82 \cdot 10^{-20} \text{ cal.}$

$1 \text{ megaelectron volt (mev)} = 10^6 \text{ ev.}$

nucleus 1.915 aum. This means that we can determine the binding energy for these

chemical elements. Their binding energy per nucleon is: deuterium - 1.09 mev,

lithium - 5.35 mev, nickel - 8.0 mev, krypton 8.7 mev, and uranium - 7.6 mev.

Table 3 shows the binding energy of the nuclei of all chemical elements per

nucleon E/A activated in the form of .. curve.
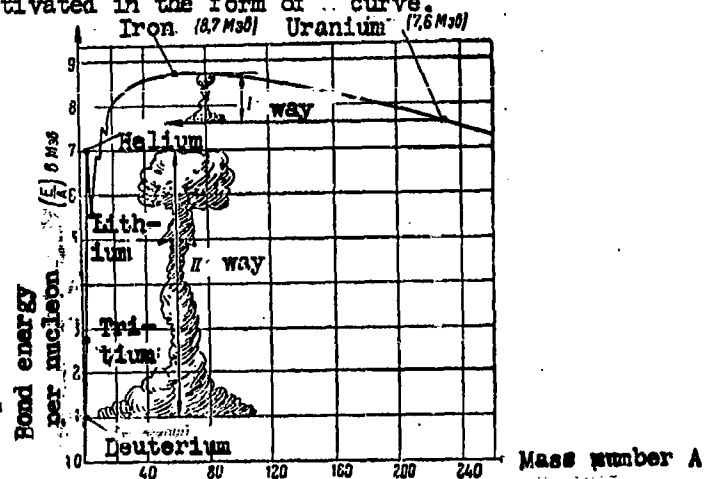
Fig. 3. Binding energy curve. Possible ways of releasing nuclear energy.

First way - fission of uranium nuclei into lighter nuclei.

Second way - FORMATION of helium nuclei from deuterium and tritium
   nuclei.

The second way is more advantageous (clearly shown by comparison of
   the explosion clouds).

In Fig. 3 the mass number A is plotted along the horizontal axis, and the

binding energy per nucleon E/A is plotted along the vertical axis in mev.

The graph shows that the greatest specific energy is released during the

formation of atomic nuclei with mass numbers 60 - 80 in the middle of the periodic

table. Atomic nuclei which come at the beginning and end of the periodic table

are formed with a smaller energy release per nucleon. The specific binding energy

curve gives a clear idea of the stability of atomic nuclei of different elements.

The stronger the nucleus, the more THE energy which has to be spent on overcoming the

attractive forces when splitting a nucleon, proton. or neutron from the nucleus.

The energy required to do this is shown in Fig. 3 for each chemical element.

This is the amount of energy per nucleon which is released when a nucleus is

formed from protons and neutrons.

-19-

Thus, the greater the specific binding energy, the more stable the nucleus. This means that the greatest stability is exhibited by atomic nuclei of elements in the middle of the table, and the least stability by those at the beginning and end of the table. This fact suggests the two possible methods of releasing atomic energy: first by the fission of the nuclei of heavy elements coming at the end of the periodic table into lighter nuclei; and second, by the fusion of nuclei of light elements (for example, hydrogen) into heavier nuclei (for example, helium).

a) Release of intranuclear energy during fission of heavy uranium nuclei into lighter nuclei.

The curve in Fig. 3 shows that the binding energy per nucleon for the uranium nucleus is 7.6 mev, while the binding energy per nucleon for iron and other closely situated elements is 8.7 mev. If we bring about a nuclear reaction in which the nuclei of the iron and elements close to it in the table are formed by uranium fission, 1.1 mev is released per nucleon, since the released energy is equal to the distance between the binding energy of the terminal and initial elements. The reverse reaction (the fusion of medium-weight nuclei into uranium nuclei) would require the same amount of energy. Let us calculate how much energy is released during the nuclear fission of 1 kg of uranium. During the fission of 1 nucleus of uranium 235 into two more or less equal nuclei, the atomic weight of each one of the lighter nuclei is approximately $235/2 = 117$. Since the binding energy per nucleon of these light nuclei is about 8.5 mev, the total binding energy of 1 light nucleus is $117 \times 8.5 = 994$ mev. But the total binding energy of the uranium 235 nucleus consisting of 235 nucleons is $235 \times 7.6 = 1786$ mev. When 1 nucleus of uranium is split into two light fragments, the energy released is equal to the difference between the total binding energy of the two new nuclei of the light elements and the total binding energy of the uranium nucleus, that is to say $2 \times 994 - 1786 = 202$ mev.

A thousand g of uranium contains $(6.02 \cdot 10^{23} \cdot 1000)/235 = 2.56 \cdot 10^{24}$ atoms. When the nuclei of all these atoms are split, the energy released is equal to
$2.56 \times 10^{24} \times 202 = 520 \cdot 10^{24}$ mev $\Leftarrow 2 \cdot 10^{13}$ cal $= 2 \cdot 10^{10}$ kilocalories

$(1 \text{ mev} = 3.8 \cdot 10^{-14} \text{ calories})$.

To make the illustration clearer, let us calculate how much TNT needs to be exploded in order to obtain this amount of energy. We know that about 1000 kilocalories are released during the explosion of 1 kg of TNT. Consequently, in our case we will need to explode a tremendous amount of TNT, about 20,000 tons.

b) Release of intranuclear energy during fusion of light atomic nuclei (hydrogen) into heavier nuclei (helium).

Let us calculate how much energy is released during the formation of helium nucleus from deuterium and tritium nuclei. The total binding energy of the deuterium nucleus consisting of two nucleons is equal to $2 \times 1.09 = 2.18$ mev, while the tritium nucleus consisting of three nucleons is equal to $3 \times 2.78 = 8.34$ mev. But the total binding energy of the helium nucleus is 28 mev. Hence during the formation of one HELIUM NUCLEUS from deuterium and tritium nuclei the amount of energy released is $28 - (2.18 + 8.34) = 17.48$ Mev.

Let us calculate the energy released during the formation of all the nuclei of the atoms contained in 1 kg of helium from deuterium and tritium nuclei.

One thousand g helium contains $(6.02 \cdot 10^{23} \cdot 1000)/4 = 1.5 \cdot 10^{26}$ atoms. Hence for the formation of 1 kg helium from deuterium and tritium nuclei the energy released is $1.5 \cdot 10^{26} \times 17.48 = 26.2 \cdot 10^{26}$ Mev $= 1.0 \cdot 10^{14}$ calories $= 1.0 \cdot 10^{11}$ kilocalories.

If we compare the calculations we made for the first and second methods of releasing nuclear energy, we see that practically five times more energy is released by the second method than by the first.

At the present time both methods are used in practice. The first method - the fission of uranium nuclei or plutonium nuclei into lighter nuclei by means of chain reactions - is used in atomic weapons and in atomic power plants; the second method - the fusion of helium nuclei from deuterium and tritium atoms by means of a thermonuclear reaction - is used in thermonuclear weapons.

3. Working principle of atomic warheads

When the nuclei of uranium or plutonium atoms are bombarded by neutrons, they split up into the nuclei of lighter elements. In the process, as pointed out, a considerable amount of nuclear energy is released.

When a neutron strikes a uranium nucleus, it excites the latter and reduces its stability. As a result the nucleus loses its spherical shape, becomes elongated and splits up into two or (very occasionally) three nuclei of chemical elements in the middle of the periodic table. For example, uranium forms pairs of nuclei of tellurium and zirconium, xenon and strontium, krypton and berium, and other elements, the product nuclei usually having different masses. These new nuclei ("fragments") are greatly overloaded with neutrons. Indeed, a nucleus of uranium 235 contains 143 neutrons, while the isotopes found in nature, for example, krypton and barium, have only 50 and 82 neutrons, respectively, or a total of 132. Consequently, the krypton and barium nuclei produced during uranium fission have eleven extra neutrons. This means that the "fragments" of fission become radioactive. They emit beta particles for the reason that some of the neutrons in the nuclei are turned into protons. But the fragments are so over-loaded with neutrons that two or three neutrons are released during fission in the free form (an average of 2.5 for each split nucleus in the case of uranium 235).

The capacity of a uranium nucleus to emit several neutrons during fission is the basis of the so-called nuclear chain reaction. The principle of it is as follows. Let us agree for the sake of simplicity that two free (secondary) neutrons appear in a piece of uranium every time one nucleus is split (Fig. 4).

By colliding with the two nuclei and causing them to split, the two secondary neutrons give rise to four free neutrons. The latter, in turn, cause the fission of the four nuclei, resulting in eight secondary neutrons and so on.

In this way, the number of split nuclei, and therefore the number of product neutrons, builds up at a tremendous rate progressing like an avalanche, without any outside interference.
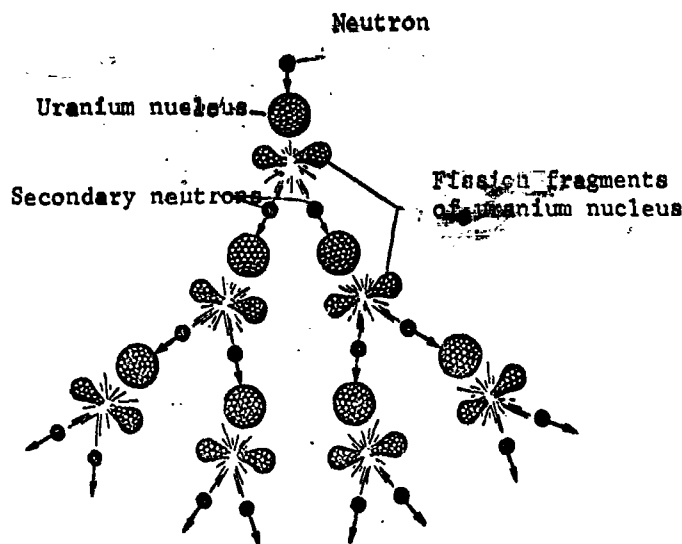
Fig. 4. Diagram showing progress of a nuclear chain reaction.

Hence the process is known as a nuclear fission chain reaction. Since it all takes place in a millionth of a second, there is in effect an instantaneous release of energy, in other words, an atomic explosion.

An enormous amount of energy is released during the explosion. As pointed out already, during the fission of the nuclei in 1 kg of uranium 235, the energy released is equal to the explosion of 20,000 tons of TNT. The power of atomic bombs is conventionally expressed in the TNT equivalent, that is to say the amount of TNT which when exploded produces the same amount of energy as the given atomic bomb.

What condition is required to bring about the nuclear chain reaction? Experiment shows that not all the product neutrons cause fission of the next nuclei. Some of them are hurled beyond the piece of uranium, while others are captured by the uranium nuclei without causing fission. Chain reactions may take place at different rates according to the proportion of lost neutrons.

If only one of three neutrons produced by the fission of a uranium nucleus causes the next nucleus to split, the chain reaction takes place at a constant rate. But if the number of new fissions is less or greater than 1, in the first case the chain reaction abates, and in the second case proceeds at an ever increasing rate and ends up with an explosion.

Consequently, to develop an accelerated chain reaction, we have to make

certain that an average of at least one neutron from those freed during the fission of each nucleus causes a subsequent fission.

The mean number of new fissions caused by neutrons from one split nucleus is termed the $BREEDING$ factor of the nuclear chain reaction. A chain reaction of an explosive nature is only possible if the multiplication factor is greater than unity. The greater the factor compared with unity, the more rapidly the nuclear reaction in the charge occurs. For example, if the multiplication factor is two, there is an average of two new fissions per one split nucleus. The number of neutrons causing fission increases in the following geometric progression - 1:2:4:8:16:32:64; The number of neutrons is doubled from one generation to the other, so that by the tenth generation there are 1024 of them, and by the eighteenth generation about 10^{24}, that is to say about as many as there ARE atoms in 0.4 kg of uranium. Thus, the rate of development of the chain reaction is a function of the way the neutrons multiply and the multiplication is described by the multiplication factor of the nuclear chain reaction.

This rate of development depends as well on the energy of the bulk of the neutrons taking part in the fission reaction, since not all the nuclei of uranium isotopes are capable of being split by neutrons. As is well known, natural uranium consists mainly of two isotopes - uranium 235 (0.7%) and uranium 238 (99.3%). Uranium 235 nuclei can be split by neutrons possessing any energy, $WHETHER$ large or small. But the uranium 238 nuclei can only be split by neutrons with energy greater than a certain strength of 1.1 mev. If the energy of the neutron is less than this, it is captured by the uranium 238 nucleus without any fission.

Even in this case, however, if the neutrons energy is greater than the threshhold value, the most probable result of collision with a uranium 238 nucleus will be inelastic scatter rather than capture. Here the neutron loses some of its energy, and at the next collision the energy will be less than threshhold. By virtue of this, the fission of uranium 238 due to neutron capture is very rare.

24

It should be pointed out that if the neutron has a fair amount of energy - more than 5 Mev, uranium 238 nuclei are split fairly effectively. This fact is applied in thermonuclear weapons to increase the power of the explosion, which will be described below.

Chain reactions are divided into slow neutron and *FAST* neutron reactions according to the energy of the neutrons taking part.

Slow-neutron chain reactions occur in nuclear reactors in which natural uranium or uranium enriched with isotope 235 are present in the form of separate blocks and are uniformly distributed through the moderator (ordinary or heavy water, or *ELSE* graphite) A nuclear chain reaction is only possible in natural uranium if the neutrons have small energy (about 1/40 ev). At such low energy the probability of fission of uranium 235 is so great that, despite the low content of nuclei, the fission of them outweighs the capture of neutrons by uranium 238 nuclei.

The purpose of the moderator is to decelerate the neutrons quickly, that is to say neutrons formed by the fission of the uranium 235 nuclei, and to prevent them being captured by 238 nuclei.

Fast-neutron chain reactions may only be attained in uranium greatly enriched with the 235 isotope, in which the neutron capture is slight on account of the low concentration.

Fast-neutron chain reactions occur in certain types of nuclear reactors and in atomic bombs.

It follows from what has been said above that the commonest uranium isotope in nature - uranium 238 - cannot be used in weapons for chain reactions. Only uranium 235 is suitable for this purpose (or natural uranium strongly enriched with uranium 235), or else artificially produced uranium 233 and plutonium. Uranium 233 is obtained from thorium, and plutonium is obtained from uranium 238 by irradiating them with neutrons in reactors.

Let us now analyze the factors on which the magnitude of the multiplication factor depends.

The multiplication factor is contingent upon a number of things. The most important of them are the type and amount of fissionable material, the shape of the charge, the material of the shell containing the charge, and the presence of impurities in the charge itself. Let us take a brief look at the effect of these factors on the development of a chain reaction in the fissionable material.

The path traversed by a neutron until its first collision with the atomic nucleus is called the free path length of the neutron. The mean free path length in fissionable material is of the order of a few centimeters. Hence, if the size of the charge, for example, the diameter of the sphere, is less than the free path length, a chain reaction is impossible (Fig. 5a). In this case the neutrons released during the fission of individual nuclei leave the charge without causing the fission of other nuclei, and are scattered into the surrounding space.

To prevent the product neutrons moving outside, and to make them cause the fission of other nuclei, the diameter of the sphere should not be less than the free path length of the neutrons (Fig. 5b). It will be clear from this that an atomic explosion can only occur when there is sufficient fissionable matter.

The least amount of fissionable material in which it is possible to have a self-sustaining chain reaction is termed the critical mass. When the mass is large, the reaction is an explosive one.

The critical mass is a function of the shape of the fissionable charge to a tremendous extent. As the charge surface increases, the weight of the fissionable material remaining the same, the proportion of neutrons which escape without splitting other nuclei increases. In view of this, the weight of the critical mass of a spherical charge which has the least ratio between the surface area and the volume is less than the weight of a critical mass of a cubic charge, and is considerably less than that of a charge in the shape of a parallelepiped. Thin sheets of wire made of fissionable material possess such an extensive surface that virtually all the neutrons formed during nuclear fission escape, as shown in Fig. 5c. Hence thin plates or wire of this kind may weigh a great deal, though the mass is less than critical. Fissionable material can be made into this shape, therefore, if it

is to be kept for a long time.
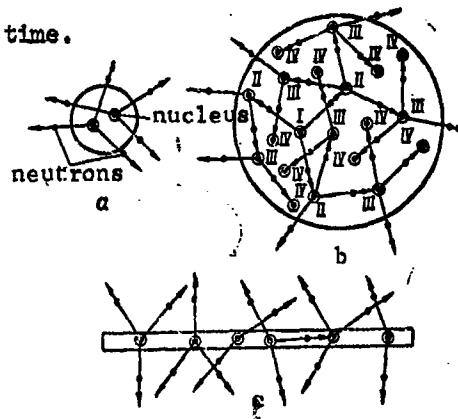
Fig. 5. Effect of shape and size of fissionable matter on development of
chain reaction: a) in small piece of fissionable material, even if the
charge has the most advantageous shape, a sphere, there is no chain
reaction; b) in the charge the fissionable material is spherical in
shape with a diameter several times greater than the mean free path
length and the chain reaction develops quickly; c) no chain reaction
develops in a thin plate of fissionable material.

For example, a rectangular plate 0.5 x 40 x 25 cm in size with a volume of
500 cm has a surface of 2065 cm. A sphere of the same volume (with a radius of
about 5 cm) has a surface of about 314 cm. As can be seen, for the same volume
(mass) the surface of the sphere is considerably smaller than for a thin plate.
Hence, the leakage of neutrons into the surrounding space is considerably less
in the case of a sphere than a thin plate.

This means that the MULTIPLICATION factor of a sphere is equal to unity at a
considerably smaller mass than some other shape. In other words, the critical mass
is least when the fissionable material is spherical in shape. Calculations show
that for uranium 235 the critical mass in this case is several tens of kilograms
(data given below).

The special casing (neutron reflector) placed around the fissionable charge
has a substantial effect on the   multiplication factor and the critical
mass. The casing is intended to bring back neutrons escaping from the fissionable
material to the nuclear reaction zone. By bringing back some of the escaping

-27-

neutrons, to the reaction zone, the reflector steps up the multiplication factor and reduces the critical mass of the fissionable material.

The presence of impurities in the fissionable material also has a considerable effect on the multiplication factor. As the amount of impurity is increased, the multiplication factor is decreased and the critical mass is increased. When there is a large amount of impurity, the latter may absorb such a large number of neutrons freed during the fission of heavy nuclei that an explosive chain reaction becomes impossible.

The critical mass also depends on the density of the fissionable matter. As already pointed out, the linear dimensions of the critical mass should be comparable with the mean free path of the neutron, which is inversely proportional to the number of nuclei contained per unit volume of fissionable material. In going from linear dimensions to mass it may happen that the critical mass of the charge without a reflector is approximately inversely proportional to the square of the density of the fissionable material. This means the density is doubled, the critical mass is reduced by a factor of four.

Conversely, if fissionable material with a mass greater than critical is expanded, which actually happens when the temperature and pressure are raised during the fission process, there is a reduction in density causing the mass to become subcritical and thereby halting the incipient chain reaction. A chain reaction can also be moderated by fission products, many of which can absorb neutrons to a great extent.

In every atomic bomb some of the fissionable material - at least as much as the critical mass - is inevitably lost (does not undergo fission)[1]. This means that small-caliber atomic bombs are less economical in the use of fissionable material than large-calliber bombs.

Thus, the above factors appreciably increase the critical mass of the original amount of fissionable required to cause a nuclear explosion. In order to use up more fissionable material, we can apply the relationship between critical

-28-

mass and density. This can be done if at the beginning of the fission reaction the nuclear charge is subjected to intensive compression of approximately a million atmospheres, as a result of which the density is roughly doubled and the critical mass correspondingly reduced by a factor of four.

It is mentioned in foreign literature that this tremendous pressure is produced by exploding a spherical shell made of conventional explosive, inside of which the nuclear charge is contained (an internally directed explosion). When the shell explodes, the gases speed towards the center of the sphere and press on the nuclear charge. This method of obtaining a critical mass is known in literature as the implosion principle. Atomic weapons based on this principle are termed subcritical in the foreign press. In subcritical atomic weapons it has been possible to bring about a considerable increase in the percentage of fissionable material used. It is pointed out that the method has been used to successfully increase the material experiencing fission to 20% or more, instead of the 2 - 5% in the first atomic bomb.

It should also be pointed out that success in producing an atomic explosion is also GOVERNED BY extraordinarily high rate of build up in the fast-neutron chain reaction. If the reaction rate were not as high, the exceptionally large accelerations (of the order of 10^{12} m/sec^2) which are imparted to the bomb casing would result in considerable expansion causing the density of the fissionable material inside to decrease. This in turn would lead to cessation of the chain reaction for reasons already pointed out.

At the tremendous pressures created during nuclear explosions, the rate of destruction of the shell containing the fissionable material in compact form is only a function of its mass (that is to say, its inertial properties); the strength of the material of the shell is insignificant. The critical mass for the material used as the charge is also a function of its ability to be split by neutrons with different energies. It has been found that uranium 233 and plutonium are more capable of this than uranium 235, hence the critical mass of uranium 233 and plutonium charges is less than uranium 235.

Let us cite some data on critical masses.

At the present time a certain amount of data on the critical masses of fissionable material has been published in foreign literature. The most detailed facts are given for charges consisting of uranium 235. For example, according to "Nucleonics," No. 6, June, 1957, the critical mass of a spherical charge (93.5% uranium 235 and 6.5% uranium 238) had a density of 18.8 g/cm³ and is 48 kg. The radius of this spherical charge is about 8.5 cm. A neutron reflector can reduce the critical mass several times. According to Table 1 in the same journal, the most effective reflectors are made of beryllium, tungsten and natural uranium. Graphite, copper, iron, aluminum, zinc and other materials can be used as less effective reflectors.

Even when a fairly thick iron reflector is used (about 10 cm), however, the critical mass can almost be halved, as shown as follows from Table 1.

Table 1.

Critical Mass (in kg) of spherical charge of uranium (93.25% uranium 235 and 6.5% uranium 238) with reflector.

Reflector Material	Density of reflector material g/cm³	Thickness of reflector	
		5 cm	10 cm
Beryllium.	1.84	20.8	14.1
Natural uranium...	19.0	23.5	18.4
Tungsten...	17.4	24.1	19.4
Graphite...	1.69	29.5	24.2
Copper...	8.88	25.4	20.7
Iron...	7.87	29.3	25.3
Aluminum...	2.7	35.5	32.0

The article in Nucleonics also implies that the thickness greater than 10 cm in a reflector is undesirable from the standpoint of reducing the crystal mass, since a greater thickness does not bring about any substantial increase in the efficiency of the reflector.

The Journal prints a graph (Fig. 6) illustrating the effect of the percentage content of uranium 235 on the critical mass of a spherical charge with and without

a reflector. It is worth noting that when the uranium 235 concentration is less than 6%, a self-sustained, fast-neutron reaction is impossible, no matter how great the mass of the charge. This also implies that a self-sustained reaction is all the more impossible in natural uranium which only contains about 0.7% uranium 235. At the same time, in slow-neutron reactions, (because of the special moderator introduced into the nuclear fuel), even when the enrichment of the natural uranium is comparatively slight, the critical mass may be several kilograms. But a slow-neutron reaction, despite the fact that the consumption of uranium 235 can be cut down sharply, cannot be employed in nuclear weapons because of its slowness.
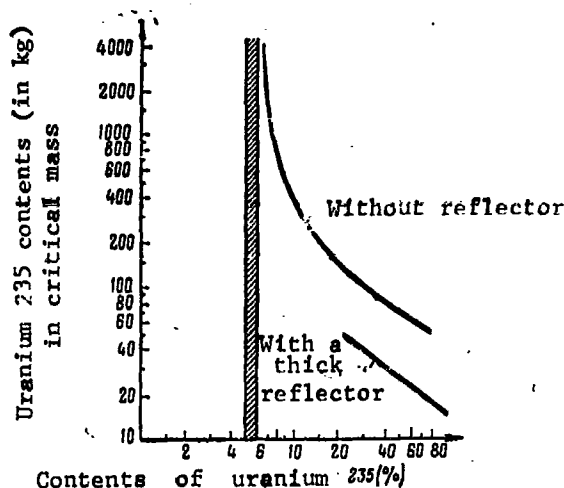
Fig. 6. Uranium 235 content (in kg) in critical mass as a function of its
       concentration (in percent).

The foreign press states that as the density of the fissionable material is increased, the critical mass of the charge with a thick reflector varies in inverse proportion to the density to the power of 1 or 2, that is to say rather more slowly than for a naked charge.

Very little data has been published on the critical mass of plutonium and uranium 233. We only know that their critical masses are approximately equal and constitute about 5 - 6 kg[1] for a naked charge. If a tamper/is added, the critical mass of these materials is reduced in approximately the same proportion as for

1/ F. Ren. The Atomic Problem. Translation from
French. For. Lit. Press. 1958.   -31-

uranium 23:.

Construction of the atomic charge. The atomic explosion is brought about by transferring the charge from a subcritical to a critical state, or more exactly, to a supercritical state. One version of the atomic warhead can be imagined to be as follows. Up to the moment of explosion, the total charge of the bomb may be divided into two or more parts; the size of each part is less than critical, thus preventing premature explosion of any of them. To bring about the explosion, all the parts of the charge have to be combined into one. They have to be brought together very quickly so that the energy released at the beginning of the reaction should not cause the unreacted parts to be blown to pieces. This conditions the number of split nuclei resulting/the chain reaction, and also the power of the explosion. When the masses of the nuclei charge are brought/together, the chain reaction begins at the moment there is a small gap between them, and not at the moment of contact. If they are brought together slowly, they may be destroyed through overheating and fly off in all directions; the bomb is then destroyed without having blown up. It is therefore essential to cut down the time taken by the approach by imparting a high velocity to the approaching masses. The action of the explosion of ordinary explosive can be used to combine the parts of the charge in the bomb. In order to increase the utilization of the fissionable material during an atomic explosion, it is surrounded by a neutron TAMPER and placed inside a casing made of dense material.

Fig. 7 shows a simplified diagram of the construction of AN atomic charge. The uranium or plutonium charge is divided into six parts. When the explosive is exploded, all parts speed towards the center and form an atomic charge with supercritical mass, surrounded by the reflector and solid metal casing. There is an atomic explosion. Other methods of forming the critical mass may also be used. For example, by changing the shape (linear dimensions) of a certain amount of fissionable material with a subcritical mass, the mass may be made critical or supercritical in certain instances. This happens, for instance, when we crumple

-32-

a thin spherical shell of uranium or plutonium into a ball. This can be done in the following way. Conventional explosive is placed around the thin uranium or plutonium shell and exploded at the desired moment. The gases crumple the uranium or plutonium shell into a ball, forming a supercritical mass in which a chain reaction begins and ends up by the explosion of the fissionable material.
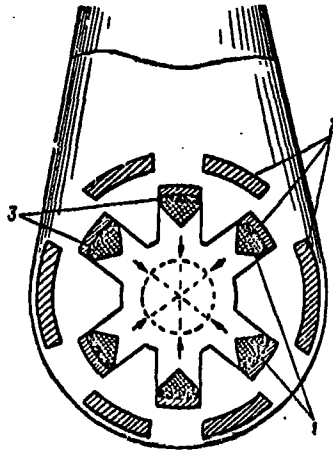
Fig. 7. Simplified diagram of atomic bomb: 1) uranium or plutonium; 2) conventional explosive; 3) neutron tamper.

To make sure the atomic charge does not fail, and to accelerate the development of the chain reaction, and therefore to increase the utilization factor of the nuclear fuel, bombs usually contain artifical neutron sources. These sources are brought into action the moment the parts of the charge combine (the moment the supercritical mass is formed) and irradiate them intensively with neutrons.

The energy produced by the explosion of the atomic charges (based on nuclear fission) may be of various kinds. According to foreign press reports, the TNT equivalent may range from 1000 to 500,000 tons. The lower limit, as pointed out, is determined by the utilization factor of the fissionable material; . in charges with the TNT equivalent of less than 1000 it is too low. The upper limit is IMPOSED by the fact that the weight of the individual parts of the charge cannot be increased to an unlimited degree, since their mass must clearly be less than critical. If we choose the system of increasing the parts of the charge,

-33-

great difficulties arise in combining them all into one at the same moment.

4. Working principles of thermonuclear charges

Nuclear weapons of a larger calliber are based on the use of thermonuclear reactions.

They are based on the formation (fusion) of helium nuclei from the nuclei of hydrogen and lithium isotopes. In the first thermonuclear bombs, only hydrogen isotopes were used as the nuclear charge. Hence they were called hydrogen bombs and they kept that name for a long time. At the present time we know of several possible fusion reactions.

The choice of one or the other is usually based on the temperature at which the reaction takes place, the duration of it and the energy yield, the aggregate state of the charge just before the reaction (liquid or solid), and other factors. It is evidently more advisable for the fusion of a helium nucleus during thermonuclear reactions to use heavy hydrogen (deuterium) and super-heavy hydrogen (tritium). The reactions takes place most rapidly in a mixture of deuterium and tritium at the same temperatures and densities. Here almost five times more energy is given off than in reaction with deuterium alone. Furthermore, high-energy free neutrons are released from the deuterium-tritium mixture and can be used to increase the force of the explosion, as will be described below. For the fusion we could also use light hydrogen atoms consisting of one proton alone. But the rate of interaction between light hydrogen nuclei at the highest temperature is so low that the reaction is not an explosive one.

Let us consider the fundamental conditions required for the formation of helium nuclei from deuterium and tritium nuclei. If deuterium and tritium nuclei

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1) According to later press reports, the TNT equivalent of an atomic device is supposed to be able to CERTAIN RANGE 50 TO 200 tons.

are brought together until the distance between them is equal to the dimensions of the atomic nuclei themselves, they come within range of the powerful nuclear forces which then combine them into a stable system - the helium atom nucleus.

The nuclear energy released during the process takes the form of the kinetic energy of the nascent helium nuclei and neutrons.

When bringing these nuclei together, considerable energy has to be spent on successively overcoming the electrostatic forces of mutual repulsion between the electron shells, and then the still more powerful electrostatic forces of mutual repulsion of the nuclei themselves. But as soon as the atomic nuclei are close together, the nuclear forces carry out considerable work. The energy released is much greater than that required to overcome the electrostatic repulsion. On account of this, the combining of deuterium and tritium nuclei, now at the incipient stage, can be further sustained and even accelerated by the surplus energy released from the fusion of the preceding nuclei. At high rates of nuclear transformation, this reaction, just as during the fission of heavy nuclei, acquires an explosive nature.

But how can we find the energy required to overcome the electrostatic forces?

It is acquired by pre-heating the hydrogen isotopes to tens of millions of degrees. During this process the atoms loose their electron shells during the very first collisions with other atoms. The result is that the material then consists of "naked" nuclei and electrons moving about independently of them. Matter in this state is said to be a plasma. The velocity of thermal motion of the particles attains such magnitude that the hydrogen nuclei can approach and combine with one another. The reaction occurring as a result of this strong heating are known as thermonuclear reactions. They take place at superhigh temperatures and pressures.

A thermonuclear reaction is very sensitive to temperature. For example, the fusion of tritium and deuterium PROCEEDS AT A TREMENDOUS RATE compared with all other thermonuclear reactions, even at one million degrees. But if the temperature

is raised to two million degrees, the reaction rate here is increased several thousand times.

At a temperature of two million degrees the energy release rate reaches the order of 10^{10} cal/sec per 1 g of mixture. The hydrogen nuclei have the least charge. Other elements have a larger charge. The larger the charge, the greater the amount of energy required to overcome electrostatic repulsion.

Consequently, to form nuclei from other, lighter elements we need still greater temperature and pressure. This makes it clear why it is hydrogen which is the most convenient substance for a thermonuclear reaction.

As has been pointed out, for the thermonuclear reaction to occur, the hydrogen isotopes have to be heated to temperatures of several million degrees. A temperature of this kind is produced when uranium or plutonium is exploded. Hence the conventional atomic charge (atomic detonator) is an integral part of the thermonuclear charges and serves as the source of super high temperature.

The principle of the hydrogen bomb is well known. The deuterium and tritium are kept in the liquid state in a tank with heat-proof casing , which serves to keep them for some time in a highly-cooled liquid state. According to foreign press reports, the heat-proof casing may consist of three layers - a solid alloy, solid carbon dioxide and liquid nitrogen. The atomic charge is placed close to the tank with the hydrogen isotopes. When the charge is exploded, the isotopes are heated up to a high temperature and the conditions are created for the thermonuclear reaction and explosion of the bomb. A hydrogen bomb containing liquid hydrogen isotopes proves impractical since it weighs too much. For example, an American thermonuclear device of this type weighed 62 tons, and could not therefore be carried by an ordinary aircraft.

Another great disadvantage in bombs of this kind is the fact that the production of tritium contained in the thermonuclear charge is an extremely complicately and costly process. Furthermore, tritium is radioactive and has a comparatively short half-life (about 12 years).

Hydrogen weapons have continually been improved since the moment they first appeared. One step in this direction was to replace liquid hydrogen isotopes by a solid deuterium-lithium compound - lithium deuteride. This immediately made it possible to reduce the size of the hydrogen bomb, since lithium deuteride is a light solid. Some of the thermonuclear charge may also consist of a compound of super-heavy hydrogen (tritium) and lithium.

Hydrogen isotopes compounded with lithium are known as lithium hydrides. The latter do not need to be KEPT IN A COOLED STATE. Furthermore, although lithium is the lightest metal, the density of lithium hydride (0.82 g/cm^3) is far greater than that of the heavy hydrogen isotopes in the liquid state (0.07 g/cm^3).

The thermonuclear reaction occurring in lithium hydride is of a complex nature. It is assumed that the lithium introduced into the charge is partially converted into tritium by the neutrons released when the atomic detonator explodes, and that the tritium then reacts with the deuterium. It is pointed out that to begin the thermonuclear reaction, the charge mixture itself can contain a small quantity of tritium. When the fusion has started, the neutrons required to produce tritium from lithium are formed by the fusion of deuterium and tritium nuclei into helium nuclei. Furthermore, the high temperature produced by the detonator ensures a direct reaction between deuterium and lithium as well as between tritium and lithium.

As soon as the thermonuclear reaction has begun, it can be sustained and even accelerated by means of heat given off by the reaction itself.

As already mentioned, when helium nuclei are formed from deuterium and tritium nuclei, the FAST neutrons escape. Hence an enormous number of fast neutrons with an energy of about 14 Mev are hurled out of the reaction zone. We may ask whether these neutrons might not be used to intensify the explosion. It seems that this is possible if the hydrogen bomb is contained in a casing made of the comparatively inexpensive natural uranium 238.

Fig. 8 shows how this charge might look. The charge is based on three phases:

-37-

fission - fusion - fission. This type of bomb is called the three-phase bomb and sometimes the hydrogen-uranium bomb in foreign literature. In this bomb the detonator first explodes (fission); then a thermonuclear reaction begins in the lithium hydride, accompanied by the release of an enormous number of fast neutrons (fusion). The neutrons cause splitting of the natural uranium nuclei, comprising the casing (fission).
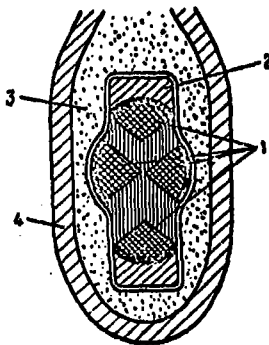
Fig. 8. Simplified diagram of thermonuclear charge based on principle: Fission — fusion-fission: 1) uranium or plutonium charge; 2) conventional explosive; 3) lithium hydrides; 4) casing made of uranium 238.

This system is more advantageous than any of the others in that the power of the bomb can be made many times greater than *by* one in which there is no uranium casing. In the case in point, as much as 90% of the energy *RELEASED* *By* the explosion can be obtained through splitting of the uranium 238. A further advantage is that the increase in the power of the explosion is brought about by relatively inexpensive material (compared, for example, with deuterium or tritium), namely natural uranium, which consists basically of uranium 238, and is used as the casing.

A casing of this kind cannot be used in the atomic bomb, since the nuclei of uranium 238 atoms only split up satisfactorily when subjected to very high energy neutrons (more than 5 Mev). During the explosion of an atomic bomb, however, most of the neutrons have insufficient energy for the fission of uranium 238 nuclei. The charge layout given above can be varied within wide limits. The

larger the caliber, the relatively larger the charge of the thermonuclear ex-
plosive and the more massive the casing, and so on. The use of uranium 238 as a
casing enables us to vary the power of the weapon from several tens of thousands
of tons to several million tons.

If the diameter of the bomb is 1 m and the thickness of the uranium casing
is 5 cm, the weight of the uranium amounts to about 3 tons. Even if only 15%
reacts when a bomb of this kind is exploded, that is to say about 500 kg of
uranium 238, the TNT equivalent is still about 10 million tons.

To produce energy with a TNT equivalent of 20 megatons, we have to bring
about the fission of 1000 kg of uranium 238. It is stated in foreign literature
that to produce the required number of high-energy neutrons, we need 20 kg of
mixture of lithium deuteride $(_3\mathrm{Li}^6 \mathrm{H}^2_1)$, during the explosion of which the energy
released is equivalent to two megatons. Thus, we see that the main source of
energy in the explosion of a bomb based on fission-fusion-fission is uranium 238.
It is pointed out that the use of a uranium casing has made it possible to construct
thermonuclear bombs with a TNT equivalent of 20 - 40 megatons. By varying the
thickness of the casing we can construct warheads of different power.

When thermonuclear bombs of this kind are tested, a great amount of radio-
active matter contamines the atmosphere and may fall onto the earth a long way
from the area of the explosion. This fact is extremely dangerous for both the
present and the future generations. In order to increase the radioactive con-
tamination of a locality during a thermonuclear explosion, foreign experts propose
that in certain cases use should be made of a thermonuclear bomb casing consisting
of material which becomes radioactive when subjected to the action of neutrons.
This matter can keep the air and the entire locality of the explosion contaminated
for a long time.

Chemical elements capable of this include cobalt, zonc, strontium, cesium
and so on. Hence, the "cobalt", "zinc" and other similar bombs are not weapons
with a new type of nuclear combustible, but thermonuclear bombs in which the radio-
active action is intensified by the inclusion of these elements in the casing.

The "clean" hydrogen bomb. Over the last few years the peoples of the world have resolutely protested against nuclear tests. They are particularly worried about the fate of   future generations on account of "contamination" of the atmosphere BY MATERIAL   resulting from the nuclear tests.

In order to distract the attention of the peoples of the world from the question of banning nuclear weapons and halting tests, American imperialist circles have put forward the idea of the so-called "clean" hydrogen bomb. The American newspaper "Washington Post and Times Herald" has commented that: "The 'clean' bomb is one which, despite the fact that its destructive power is JUST AS GREAT can be exploded in such a way that it does not disseminate the (strontium 90 which would poison the earth's 'atmosphere' in an ordinary hydrogen explosion."

Some commentators in discussing the American press statement have asked the question, how practical is the idea of a "clean" hydrogen bomb in the true sense of the word? There is only one answer: in principle there cannot be any "clean" bombs since a nuclear explosion cannot take place without the occurrence of neutrons, and the capture of neutrons by the air and earth (water) creates radioactive fallout. Nevertheless it is possible to reduce the radioactivity of an explosion to a small extent.

In order to reduce the number of fission fragments from the uranium or plutonium, which are the main sources of contamination of the atmosphere and earth during a hydrogen explosion, the design of the present hydrogen bombs has to be modified, as pointed out in the foreign press, that is to say the use of a uranium casing and an atomic detonator has to be abandoned.

Here the question arises, how can we attain the high temperature required for the thermonuclear reaction between hydrogen and/or lithium hydride? For the moment it is difficult to answer. It has been conjectured in the foreign press that it may be possible to find new ways of detonating hydrogen bombs based on the use of shockwaves from the explosion of conventional explosive.

It is pointed out that the principle of cumulation or other properties of

-40-

shockwaves could be used for this purpose. A velocity of the order of 10^7 cm/sec has been observed over a small AREA of the front of a cumulative jet with a beryllium coating WHEN [exploded in a vacuum. This tremendous kinetic energy corresponds to THE initial propagation velocity of A shockwave at an explosion temperature of about one million degrees. But the mean velocity of the cumulative jet is roughly ten times lower. Hence there are great difficulties in the way of applying the shockwave method to bring about a thermonuclear reaction. It will take time before they are finally solved.

5. Types of warfare with nuclear weapons

The various designs and caliber of nuclear warheads makes·it possible to use them in warfare for different purposes.

First of all it should be pointed out that nuclear weapons may be used for two purposes. First, they can be used directly against the enemy soldiery and armaments on the battle field. Secondly, nuclear weapons can be used to strike powerful blows against very important industrial, transport and political centers.

According to the purpose in mind, foreign experts subdivide nuclear weapons into tactical and strategic weapons.

Tactical nuclear weapons VARY IN caliber and, according to FOReign press reports, have a TNT equivalent of about 1000 to 50,000 tons. The smallest warheads can be used against the enemy's front, in anti-aircraft SHELL and also in aerial combat. It is also possible to use nuclear warheads extensively at sea, in torpedos, mines and depth charges. They can also be used on land for obstructional purposes and also for explosive operations below ground and in rock.

The WAY IN WHICH nuclear warheads ARE/ HOMED INTO military TARGETS is a very important matter. In tactical weapons the nuclear warheads may be carried by non-guided or guided ballistic missiles (rockets) of different range,/ By aircraft and also By large-caliber artillery SHELLS.

The commonest form of anti-aircraft nuclear weapon is the guided ground-to-air missile carrying a warhead similar to that used in the USA under the name of

-41-

Nike-Zeus with a TNT equivalent of about 5000 tons. At sea nuclear warheads may be carried by torpedos or even remote-controlled launches. Here great importance is acquired by submarines which can shell coastal targets with nuclear missiles both while submerged and on the surface.

There is no clear-cut line between tactical and strategic weapons. Foreign experts think that strategic problems can be solved under certain circumstances by the use of nuclear warheads intended for tactical purposes. Nuclear contingents of troops intended for use against standard strategic targets will have a TNT equivalent of 1 - 5 megatons. Finally, it is possible to have still more power- ful nuclear charges with a TNT equivalent of up to 40 - 50 megatons.

Nuclear weapons for strategic purposes will usually be carried by long- range rockets, intercontinental rockets and pilotless aircraft. The use of piloted craft is possible as well. According to foreign experts, the most effective APPLICATION of nuclear warheads when the range is more than 6000 km are multistage intercontinental rockets and single-stage rockets for ranges of about 1000 km.

Also possible in the future is the use of high-altitude balloons carried along by air currents at a height of 30 or 40 km. Reports have appeared recently in the foreign press to the effect that artificial earth satellites could be used to drop powerful nuclear bombs.

The foreign press points out that as a rule all strategic weapons can ensure the delivery of nuclear charges to the desired TARGET, area with comparatively high accuracy. THEY CAN BE MADE TO FALL WITHIN a radius OF about 1 to 20 km.

Under these conditions the use of atomic charges with a TNT equivalent of several megatons could lead to the disperson area being completely covered by the contaminated zone during the explosion. This makes it possible to hit important targets accurately, even if they are small in size, such as factories, strategically important bridges, dams and sluices, power plants and so on. Thus, present-day nuclear strategic weapons are a powerful and reliable method of striking at the

enemy and are substantially superior in all respects to the strategic aircraft of World War II.

6. Phenomena observed during a nuclear explosion

Depending on the nature of the objective and the purpose of the atomic attack, a nuclear explosion can be carried out in the air, on land (water) or under ground (under water). Accordingly, we distinguish *AERIAL*, ground (water) and underground (under water) explosions.

Nuclear explosions in the air are usually intended to destroy cities and industrial buildings, For destroying soldiers and armaments on the battle field and destroying aircraft on the ground; in these instances the explosion takes place at a height of several hundred or thousand meters above ground, according to the TNT equivalent of the charge. An aerial nuclear explosion may be used to destroy aircraft and pilotless craft in the air. In this case the explosion can occur at high altitudes above the earth's surface and is called a high-altitude nuclear explosion. round-*LEVEL* water-*LEVEL* explosions are intended to destroy stronger buildings, railway junctions, heavy shelters, airodromes and ships on the water. They can be made at an altitude *TO OCCUR* of several dozen meters above ground (water) or actually on the ground (water).

An under ground atomic explosion may be used to destroy extra strong underground constructions, aerodromes, underground factories and stores. In certain cases an underground or ground *LEVEL* explosion may be used to contaminate a locality in the enemy's rear.

An under water nuclear explosion is intended to destroy submarines, ships on the surface of the sea, and hydrotechnical constructions (dams, weirs).

As is known, the question of intercepting ballistic missiles has not yet been solved. Nevertheless, in the future it will be possible to construct special anti-rockets which will destroy ballistic missiles at very great heights *OR* in outer space. It is very probable that these rockets will have atomic warheads. Atomic explosions of this kind can be called cosmic explosions.

The phenomena observed during a nuclear explosion depends to a considerable extent on the type of explosion. At the present time the aerial explosion is the one which has been studied the most. Hence the phenomena observed during an explosion of this type will be considered by us in greater detail. An exceptionally high concentration of heat energy occurs in the chain reaction zone. The temperature rises rapidly to several tens of millions of degrees, while the pressure attains a billion atmospheres.

On account of this, by the time the nuclear reaction is over, the bomb casing and all other parts have evaporated. The vapor from the casing and the fission products from the nuclear charge heat up to a million degrees and emit soft x-rays, which are absorbed by the layer of surrounding air and heat/ THEM up to several hundreds of thousands of degrees. At the point of the explosion there occurs a bright, luminous spherical region which emits intensive luminous radiation into the surrounding space.

The entire locality of the explosion is lit by a dazzlingly bright flash (Fig. 9), the glow from which can be seen dozens of kilometers or more away.

Most of the neutrons which do not take part in the nuclear reaction, and also the gamma rays emitted during the nuclear fission are absorbed by the bomb casing. It is only relatively small proportion of them that reaches the outside space and is disseminated from the point of the explosion. The stream of gamma rays and neutrons disseminated at this point is known as penetrating radiation.

At the surface of the luminous area there is a very sharp drop in temperature and pressure. On account of the drop in pressure the white-hot explosion products begin to expand at a precipitous rate, forcing back the layer of air around the explosion point and compressing it. The compression is passed on from one air layer to another in the form of a shockwave and spreads a considerable distance from the original point of explosion.

At short distances from the point of explosion the shockwave front is at the same time the surface of the luminous region emitting powerful luminous

-44-
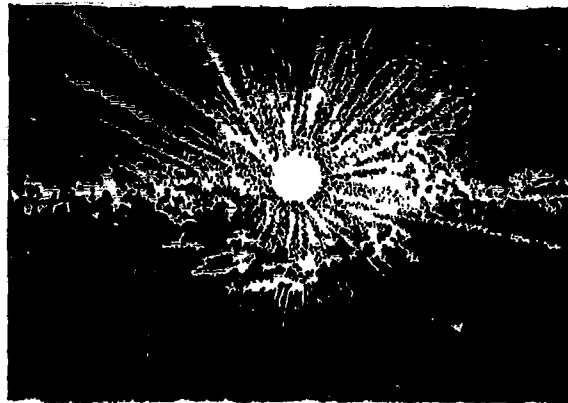
Fig. 9. Flash during aerial atomic explosion.

radiation into space. The white-hot explosion products in the middle of the luminous region are a source of intensive gamma radiation emitted during the decay of the radioactive fission products.

About two hundredths of a second after the explosion of an intermediate nuclear bomb, the shockwave front is about 100 m away from the center of the explosion.

As it moves away from the center, the air temperature at the front is reduced and finally reaches the point where the air ceases to be luminous. After this, it is the surface of the white-hot gases which becomes the source of light. The radius of the luminous region of white-hot gases rapidly increases and about a second after the explosion attains about 150 m. The size of the luminous region then increases comparatively slowly, and the temperature of its surface falls, the power of the luminous radiation also decreasing. The action of the luminous radiation ceases roughly two or three seconds after the explosion.

The density of the gases in the luminous region is below that of the surrounding air on account of high temperature. Hence the region moves upwards very quickly, like a balloon. Approximately ten seconds after the explosion the luminous region is entirely extinguished.

When the explosion products rise up, they form a rising air stream which carries up the dust lifted from the surface of the earth by the shockwave.

A column of dust is created in the region of the epicenter of the explosion and rapidly rises upwards.[1]

The explosion products during this time continue to be a source of radioactive emission.

As they rise, they cool down and turn into a swelling cloud of radioactive smoke, which gradually increases in size. On further cooling, the water vapor contained in the air condenses on the surface of the cloud of smoke. The condensate quickly envelopes the cloud, which now looks like an enormous ball of cotton. The column of dust rising from the earth continues rapidly growing, reaches the cloud and forms the characteristic mushroom (Fig. 10).

The mushroom cloud formed during an intermediate bomb explosion attains a height of 10 - 15 km in about 10 or 12 minutes. Here the diameter extends for several kilometers. It then gradually loses the characteristic shape and disperses, moving in the direction of the wind. Some of the explosion products settle on the surface of the earth in the explosion area and in the wake of the radioactive cloud, causing radioactive contamination of the locality.

The size of the cloud formed during the nuclear explosion, its rate of ascent and altitude increase with the poer of the explosion. If the explosion takes place at a high altitude, the column of dust may not join up with the cloud of smoke.

A nuclear explosion is accompanied by an abrupt sound reminiscent of a loud peal of thunder. It can be heard for tens and hundreds of kilometers. A nuclear explosion is |accompanied FURTHER . by radiowaves which can be received by radio stations in the form of signals.

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[1] The epicenter of the explosion is a point on the surface of the earth directly underneath the center of the area of explosion.
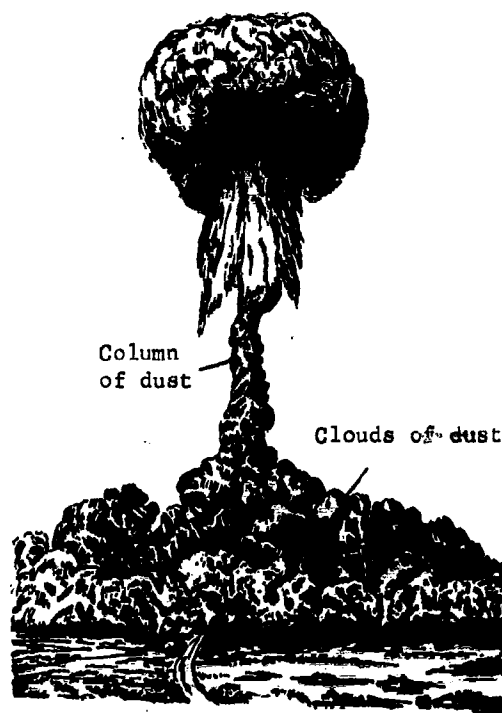
Fig. 10. Mushroom cloud during atomic explosion.

The pattern of the explosion of a hydrogen bomb in the air is similar to that of an atomic bomb. But on account of the greater power of hydrogen bombs, the VISUAL effects accompanying the explosion all look much more impressive. IN AN explosion on the ground, the luminous region is semi-circular in shape (Fig. 11). At the point where the region comes into contact with the ground surface, the upper layer of the ground is fused and turns into slag when it cools.
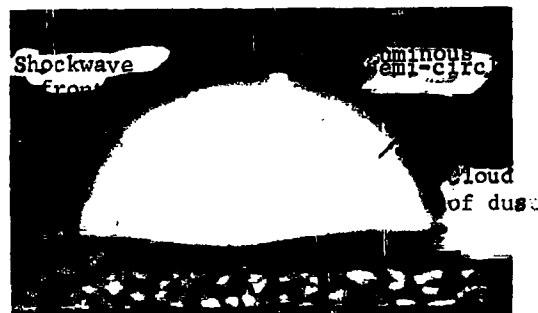
Fig. 11. Luminous semi-circle caused by atomic bomb on the ground.

The intensity of the luminous radiation is less in a ground explosion than in an aerial one, since the semi-circle is partially screened by dust raised by the shockwave. A large amount of dust is sucked up by the cloud during a ground explosion. The dust and nitrogen dioxide give the cloud a brownish color. The amount of dust in the cloud depends on the height at which the nuclear bomb was exploded. If the ball of fire touches the ground, a considerable amount of soil is evaporated and carried away by it. This can be illustrated with the following figures.

The energy required to heat up and evaporate sand, which can be considered a typical representative of the soil components, is about 2700 cal/g. Hence if 5% of the energy of a nuclear bomb (with a TNT equivalent of 20,000 tons) is used on evaporating the soil, about 360 tons of sand is contained in the atomic cloud in a gaseous state.

Some of the fallout produced by a ground explosion mixes with the fused soil turning the latter into radioactive slag, and also settles on the surface of the earth. This causes greater contamination of the locality in the area of the explosion, compared with an aerial explosion. A CRATER may be formed at the site of the explosion.

In an underground nuclear explosion, strongly heated gaseous products create enormous pressure on the soil as they expand. This leads to the formation of a strong shockwave underground, which causes vibration in the surface layer of the earth as it spreads, similar to an earthquake.

A huge CRATER is formed at the point of the explosion and its size depends on the power of the warhead, the depth of explosion and the type of soil. The soil thrown up from the CRATER (Fig. 12) mixes with the fallout, settles on the earth and covers the locality with a layer several tens of centimeters thick. On account of this radioactive contamination of the locality is considerably greater in the region of the CRATER during an underground explosion than in one in the air or on the ground, although the area of the contamination is smaller.

-48-

There is much less penetrating radiation and, particularly, luminous radiation during an underground explosion than during aerial or ground explosions.

In an underwater nuclear explosion, the white-hot explosion products form a luminous region under the water in the form of a gas bubble. A brightly illuminated spot appears on the surface of the water at the point of the explosion. The thermal energy radiated by the luminous region is used basically to heat up and evaporate the water in the explosion zone.

Fig. 12. Underground explosion.

The sudden expansion of the explosion products and water vapor causes a powerful shockwave in the water. When an atomic bomb is exploded under water not too far below the surface, a column of water more than a kilometer high is thrown up. Above the column of water there forms a cloud, consisting chiefly of water vapor, which increases in size until it attains several kilometers in diameter (Fig. 13). The water begins to fall back several seconds after the explosion. Here an enormous cloud consisting of fine drops (spray) is formed at the base of the column. As the water falls back, the cloud (which is sometimes called the basis wave) spreads outwards and rises to a considerable height within minutes. The speed of propagation of the cloud is at first several tens of meters a second, after which it rapidly drops. The motion of the cloud then CEASES. The cloud

produces radioactive rain.

An underwater explosion is also accompanied by a formation of ordinary waves on the surface of the water. These waves may be as high as 20 or 30 m a short distance from the point of the explosion. As they move away from the latter, the height of the waves rapidly decreases and does not exceed 2 to 4 m at a distance of 10 km. If the underwater explosion is carried out in a shallow reservoir, a large CRATER is formed on the bottom. In this case a considerable amount of soil is carried up into the air with the water.

When considering the phenomena occurring during an atomic explosion, it is not difficult to see that the effect of atomic weapons is to produce a powerful shockwave, intensive luminous radiation, gamma radiation and a neutron FLUX and also radioactive contamination of the locality. Here we should distinguish the following harmful factors in an atomic explosion: shockwave, luminous radiation, penetrating radiation and radioactive contamination. Thus, as distinct from conventional explosives, an atomic explosion is characterized by a combined destructive effect.

Let us take a look at high-altitude and cosmic explosions. The outward appearance of a high-altitude nuclear explosion is similar to the aerial explosion. The only difference is that there is no column of dust raised from the earth. There is a ball of fire and a cloud of curly smoke.

An aircraft in flight can be put out of action during a high-altitude explosion through destruction of the aircraft itself or the loss of the crew. The structure of the aircraft may be destroyed by the shockwave and luminous radiation, and the crew may BE KILLED BY THE penetrating radiation. Thus, the shockwave, luminous radiation and penetrating radiation are the destructive factors in a high-altitude atomic explosion.

A cosmic nuclear explosion takes place at an altitude at which the density of the air is virtually zero. In this case the energy of the explosion is only transferred to the material making up the atomic charge and the devices related

-50-

to it, for example, the rocket carrier. The whole of the material is heated up to a tremendous temperature, evaporates and turns into highly ionized gas called plasma.

As distinct from all other types, during a cosmic explosion a considerable amount of energy is radiated into surrounding space in the form of light, ultra-violet and soft x-rays. The two latter types of radiation are absorbed by the air surrounding the point of the explosion during ground, aerial and high-altitude explosions.

When they act on A flying craft, all these types of radiation are absorbed by it and heat it up to a high temperature. Since the cosmic explosion occurs in airless space, there is no shockwave. Here the destructive factor is radiation a wide wave band, the shortwaves being the most intensive.

Certain other features of a cosmic nuclear explosion are of interest.

The atomic nuclei and the electrons detached from them at very high temperatures travel freely in all directions because there is no barrier around the charge to prevent them doing so.

Thus, streams of particles with an electric charge escape from the center of the nuclear explosion: the atomic nuclei carry positive charges (positive ions) and the electrons carry negative charges (negative ions).

These particles move through the earth's magnetic field, provided the explosions have not taken place further than several earth radii away, that is to say, within 20 or 30,000 kilometers and not below 150 - 200 km. This is due to the fact that the particles move freely without loosing their electric charges. Every electrically charged particle moves through a magnetic field

corkscrewing round the lines of force. The size of the terms in the case in point with the velocity of the particle and its mass.

Calculations show that at heights not exceeding several thousand kilometers, the dimensions of the terms described by particles hurled outwards by a nuclear explosion range between several hundred meters and several tens of kilometers.

-51-

These dimensions are extremely small compared with the diameter of the earth. This means that virtually all particles produced during a nuclear explosion move along the lines of force of the earth's magnetic field. Approximately half of them move towards the Northern hemisphere and the other half moves towards the Southern hemisphere. The particles move as though they were inside a magnetic tube with a diameter of not more than 100 km.

In the long run these streams of particles reach the denser layers of the atmosphere and are absorbed at a height of about 150 km. They cause strong ionization of the atmosphere over an area of many thousands of square kilometers and cause intensive aurora borealis, accompanied by strong magnetic storms, and atmospheric disturbances of radio communications and radar.

In March-April, 1959, the foreign press wrote a great deal about such phenomena in connection with experiments carried out by the U.S. Armed Forces in the Pacific (in the region of Johnson Island) and in the southern part of the Atlantic. The explosions were carried out at altitudes at the order of 480 km, the charges being carried to this height in rockets.

These experiments fully confirmed the above-described picture of the nuclear explosion in outer space.
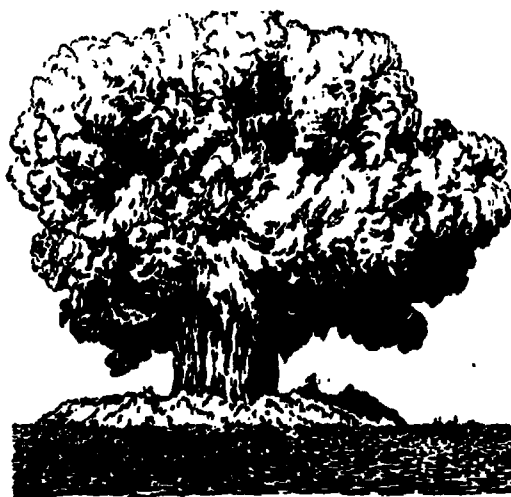
Fig. 13. Appearance of underwater explosion.

CHAPTER II

SHOCKWAVES FROM NUCLEAR EXPLOSIONS

1. Occurrence of air shockwaves during explosion.

Different ways in which the explosions acts over distances. Shockwaves occurring during nuclear explosions have a great deal in common with shockwaves from conventional explosions. Hence the principal properties and mode of origin of these waves can conveniently be considered first in the case of the explosion of conventional explosives.

First of all it must be taken into account that during an explosion, explosives are virtually instantaneously turned into gas. At first the gas possesses very high pressure and is heated up to a high temperature. Explosive gases therefore expand at very great rates (up to 5 or 8 km per second under certain conditions). If the stream of fast-moving, fairly dense gas encounters any object in its path, it strikes it with great force and may destroy it. This is one way in which an explosion is effective at a distance, i.e. THE EFFECT of expanding explosion gases.

But if the explosive charge is contained in a fairly strong casing, for example, a steel shell or bomb, the first obstacle encountered by the gases is a metal wall. In this case the gases, when they expand, may exert an extremely high pressure on the walls, measured in tens or hundreds of thousands of atmospheres. This pressure is sufficient to destroy the casing of the shell or bomb in its entirety and to turn the metal casing into comparatively fine fragments. The fragments are hurled outwards by the explosion products (expanding gases) at extremely high velocities (1-2 km per second). Many of the fragments transfer some of the explosion energy as well. Thus they may fly much further than the expanding gases and may have a very harmful effect on people, animals and equipment. Flying splinters make holes in thin armor; if they pass through fuel containers, the splinters may set fire to it and spray in all directions. The very fast moving fragments may penetrate/into explosive material and detonate it. Thus these

fragments also help to spread the destructive effect of the explosion.

Finally, as they move, the expanding explosion gases force back the medium around the charge and form a so-called shockwave.

The mechanism of the formation of an air shockwave during a conventional explosion can be imagined in the following way. The explosion turns the solid (or liquid) explosive into a gaseous state /WITHIN an extremely brief interval of time. The gases formed possess extremely high temperature and are at very high pressure. As they try to expand, they cause a sharp impact on the surrounding layers of air, compressing it and heating it up to a high temperature. Being strongly compressed and striving at the same time to expand, the compressed layers of air exert a sudden pressure on the neighboring layers, compressing them in turn. These layers, in trying to expand, do the same, and so on. Thus, the process of propatation of a high pressure (temperature and density) takes place in the air at supersonic velocity. This spasmodic variation in pressure (temperature and density) spreading through the air at supersonic velocity is in fact an air shockwave. It is the third form in which the effect of the explosion is transferred.

The shockwave is mainly formed in this way both in air, as well as under water and underground. During an explosion underground, however, the long-range effect of the explosion in the form of a compression wave is distinguished by certain features.

Thus, there are three principal WAYS IN WHICH the effect of the explosion by is carried over a distance, i.e., explosion gases, splinters from the charge casing and the shockwave.

Besides the principal carriers of the explosive effect, there may also be random ones, for example, local objects, stones, lumps of earth, MASONRY, and so on, which may be torn from the point of explosion and may acquire considerable velocities. The impact of such objects may also cause damage. THE/ IMPOSSIBILITY OF THIS has to be taken into account in practice.

In cases in which the explosion is a nuclear one, energy is transferred to

-54-

surrounding space both by the above-described carriers as well as in the form of luminous and nuclear radiation.

The shockwave as the principal carrier of the explosive effect of powerful charges in air and underwater. The importance of the above-described carriers is not the same.

Fragments may be important when the charge casing has thick walls and when the weight of the metal of the casing is several times greater than that of the explosive charge. This happens in fragmentation and demolition shells and bombs. But if the casing is thin, the splinter effect is insignificant and a large proportion of the energy of the explosion is transmitted to the shockwave. In this case the latter becomes the principal carrier. During the explosion of nuclear charges, the energy released is so great that there is total evaporation of the casing and the entire charge mechanism, resulting in incandescent gases instead of fragments; the gases only expand over comparatively short distances. Hence their effect over more appreciable distances disappears, and it is then the shockwave which becomes the basic carrier.

If we consider a medium such as water, we deal with a substance which hampers the explosion gases and fragments much more intensively than air. In view of the fact that the density of water is much greater than that of air, the mass of water set in motion by the shockwave is many times greater than that of the air in an air shockwave.

A similar effect occurs during underground explosions when compression waves are formed in the earth.

Thus it follows from consideration of the methods by which the effect of the explosion is transferred over a distance that the most substantial way is the shockwave, particularly the air shockwave. This results from the fact that the objects and construction usually destroyed by an explosion are situated in an air medium and that charges such as PoWERFUL CONVENTIONAL demolition bombs, atomic and hydrogen bombs are intended first and foremost for detonation in the air.

<u>Formation of shockwave by conventional explosive.</u> Let us first consider
how the air shockwave occurs during an ordinary explosion.

The explosives (TNT, etc.) used in industry and in warfare are fairly
complex chemical compounds.

Explosion of the detonator forms gases which impact upon the layers of
explosives surrounding the detonator with great force. As a result the molecules
of explosives are set in very fast motion, begin to collide with one another and
undergo changes.

The physical-chemical transformations cause the explosion gases to be formed
by the charge; here a great quantity of energy is given off and the carriers of it
are fast moving molecules of explosion gases which are subjected at first to very
high pressures.

The transmission of the explosive decomposition through the bulk of the
charge is termed detonation. The rate of propagation of the detonation is extremely
high and ranges from 4 to 8 km/sec. The greater the detonation rate, the more
powerful the explosive and the greater the gas pressure obtained during it.

The pressure of the explosion gases at the moment they are formed is expressed
by the equation

$$P = \gamma \, \frac{D^2}{40}.$$

Here P is the pressure in kg/m^2 in the decomposition zone of the explosive;

γ is the specific weight of the explosive in kg/m^3;

D is the rate of propagation of detonation in m/sec.

This equation can be used to determine, for example, the pressure of the
explosion gases produced during the explosion of the commonest explosive, TNT.
In TNT the detonation rate is 7200 m/sec, and the specific gravity is approximately
1600 kg/m^3. Consequently,

$$P = \frac{1600 \cdot 7200^2}{40} = 2\,073\,600\,000 \ \text{kg/m}^2$$

or 207,360 kg/cm^2, which is 200,000 atmospheres to the nearest round figure.

This tremendous pressure cannot be withstood by any barriers. As a result,

the explosion gases begin to expand in all directions. If the explosion occurs in
air, the gases begin expanding in all directions with an initial velocity close to
the detonation rate.
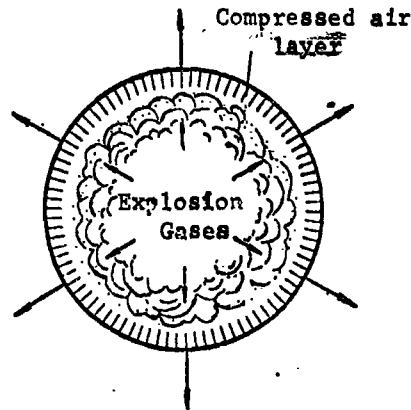
Fig. 14. Expansion of explosion gases in formation of air shockwave.

As they expand, the gases push back the surrounding air, during which the
air layer next to them begins itself to move at the same velocity as the gases.
This velocity is many times greater than the speed of sound in air, which is
approximately 340 m/sec. The air forced back by the explosion gases is strongly
compressed and heats up to a high temperature. The outside boundary of the
compressed air rapidly moves forward at a velocity greater even than that of the
gases, and moves further and further away from the boundary of the gases, as shown
in Fig. 14. This means that the rate of shift of the outside boundary of the
compressed air exceeds the expansion rate of the explosion gas boundary.

The outside boundary of the compressed air possesses certain very important
features. First of all it should be noted that it is a very clear-cut one. If
the compressed air zone is illuminated by a brief flash from an electric spark,
an extremely clear photograph can be obtained of it, despite the great velocity of
the compression zone. Photographs of this kind show that the compressed air zone
is like a thick-walled glass sphere. The shifting region of strongly compressed
air spreading outwards from the center of the explosion at supersonic speed is
called the air shockwave, and its leading boundary, on which there is a sharp

discontinuity in the air density, is called the shockwave front. This compression is rapidly transmitted from one air layer to another.

As long as the compressed air region is supported by expanding explosion gases, however, it cannot be considered to have definitely formed.

As the explosion gases expand, the velocity of their own motion decreases. The energy from the gases is transferred to the MOVING PAIR. The velocity of the explosion gases ¡approaches zero and their pressure drops below that of the surrounding atmosphere on account of extreme expansion. No longer supported from behind by the gases, the air shockwave becomes detached from them and continues moving by inertia.

In the rear, however, the compressed mass of air begins to expand in a backward direction, towards the rarefied gases. A rarefaction zone is created behind the region of strongly compressed air, that is to say a region in which the air pressure is below that of the surrounding atmosphere.

In the densified region the air moves in a forward direction. In the rarefied region, on the contrary, there is motion of the air in a backward direction, towards the center of the explosion. This is shown in Fig. 15. Since all gases are heated up when compressed, the air, too, in the compression region has a higher temperature. Conversely, in the rarefaction region, (for weak shockwaves) the temperature of the air is below that of the unperturbed atmosphere.

Theory and practice show that in the case of a fully formed air shockwave, which has detached itself from the explosion gases engendering it, the greatest pressure, velocity and temperature of the air are observed right behind the shockwave front, that is to say, behind the discontinuity in the air density. It is sometimes said that the maximum pressure of a shockwave is the pressure at its front.

The shockwave front spreads at a velocity exceeding the speed of sound in air. Here the velocity of the front increases with the pressure. If the pressure at the front approaches that of the unperturbed atmosphere at a very great distance from the site of the explosion, the velocity of the front approaches the

-58-

speed of sound and the whole of the shockwave becomes an ordinary sound wave.
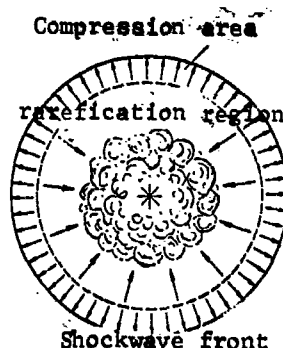
Fig. 15. Formation of air shockwave and detachment of explosion products.

As distinct from the shockwave front, the boundary separating the compression area from the rarefied area moves at the speed of sound (strictly speaking, at a speed slightly greater than sound). The velocity of the "tail" of the compression area is equal to the speed of sound in/ ᵀᴴᴱ medium heated by the compression region. As a result the wave front moves away from the boundary between the compression and rarefaction region, and the width of the compression region increases more and more as the wave moves on. The width of the compression region is frequently termed the depth of the shock wave.

Formation of an air shockwave during a nuclear explosion. In a nuclear explosion there is a release of a tremendous amount of thermal energy capable of melting and turning into an extremely hot gas both the nuclear charge, the surrounding casing and all the construction parts in direct proximity to the parts. The air AROUND the charge is also made extremely hot. A

A fireball forms at the point of the explosion and increases very rapidly. The boundary of the fireball moves along, encompassing more and more masses of the medium, for example, the air. But beyond the boundary of the fireball the medium remains completely motionless for some time, until it is drawn inside the ball.

The larger the size of the fireball becomes, that is to say, the greater the amount of the surrounding medium drawn into it, for example, air, the lower the temperature inside the ball, since the energy it has received from the explosion

is distributed through an ever-increasing mass. Some of the energy escapes from
the ball as a result of luminous and penetrating radiation. In short, some photons
are detached from the inside of the ball and spread/over a very large distance.

These factors cause the ball to cool down; the strength of the molecular
impacts is weakened, the electrons are again trapped by the atoms and become part
of their electron shells, while the atoms recombine into molecules. The rapid
energy carriers - the photons and electrons - become smaller and smaller in number,
and the principal carrier of the remaining energy of the explosion is the molecule
of the surrounding medium, now moving comparatively slowly (at hundreds OR tens
of kilometers per second, which is thousands or even tens of thousands of times
slower than the speed of photons).

Under these circumstances the very hot gas cloud from the nuclear
explosion has similar properties to the cloud of explosion gases produced by con-
ventional explosives.

As we have already pointed out, as this cloud expands outwards, it forces
back the surrounding air and compresses it, increasing the pressure.

The temperature of the fireball, however, is still several thousand
degrees and it continues to glow very brightly. The light from the fireball now
passes through the region of strongly compressed and heated, though poorly luminous,
air. This air absorbs the light to a very great extent. Hence when the strongly
compressed air shell forms around the fireball, its luminescence is somewhat reduced
at distant points in space.

The compressed air shell rapidly expands, its pressure decreasing strongly
during the process. For example, IF the radius of the shell is doubled, the
pressure IS eight times/ $LOWER$. Here the transparency of the air is increased,
and if the explosion occurred in the air, the luminosity of the fireball is again
intensified.

The compression zone formed corresponds to the shockwave and its front
boundary to the shockwave front.

As the fireball expands and the shockwave is formed, the energy of the ball which has not yet been removed   By   the radiation, is transmitted to the wave. The fireball eventually ceases   expanding and the shockwave is detached from it. This means that the wave moves on by inertia and the elasticity of the medium set in motion.

What has been said suggests the following. Expansion of the fireball and the motion of the shockwave in the medium divide up in time into three different stages:

1) expansion of the fireball, principally due to the transfer of energy by photons and electrons without the formation of a shockwave outside the ball;

2) expansion of the fireball with formation of a surrounding, strongly compressed layer of medium moved by the pressure of the expanding ball;

3) motion of the shock   through the medium, irrespective of expansion of the ball, which gradually / *Die* away.

These three stages are shown diagramatically in Fig. 16.

The dimensions of the luminous region occurring during a nuclear explosion are comparatively small. For example, in an intermediate nuclear explosion, the diameter of this region is not more than 300 m. The destruction zone caused by the mechanical action of the explosion, however, is approximately ten times greater. The main mechanical destructive effect in this case is caused by the air shockwave.

During an explosion in a denser medium, for example, water, the size of the fireball is approximately ten times smaller than in air, whereas the size of the destruction zone is only slightly less than in air. The significance of the shockwave in an underwater explosion is less than that of the shockwave in air.

On the basis of these facts a more detailed study of the characteristics of shockwaves produced by nuclear explosions is of prime importance in correctly understanding the destructive effect of nuclear explosions and methods of/*PROVIDING* protection from them.

-61-
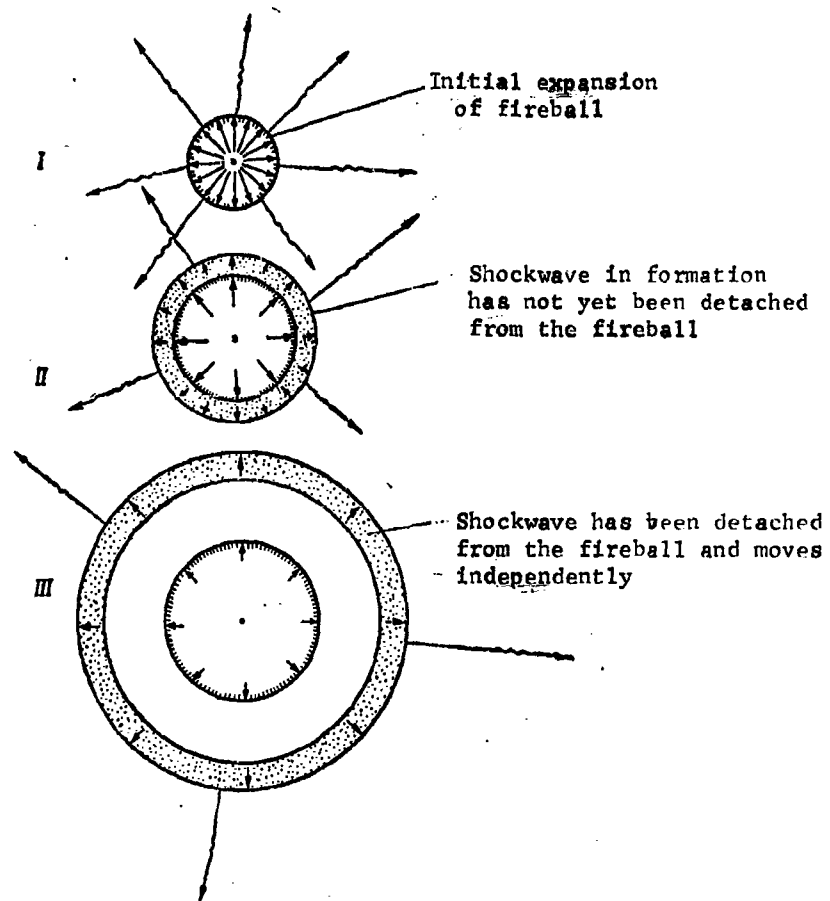
Fig. 16. Three principal stages in expansion of fireball and formation of shockwave.

2. Basic Properties of Air Shockwave

In order to gain a better idea of the properties of the air shockwave, let us consider the following case of an explosion. Let us say that the nuclear explosion has occurred close to the surface of the earth and that the air shockwave spreads over the surface, forming a kind of _DOME RESTING_ on the ground. This is shown in Fig. 17.

Air shockwave front

Surface of the Earth
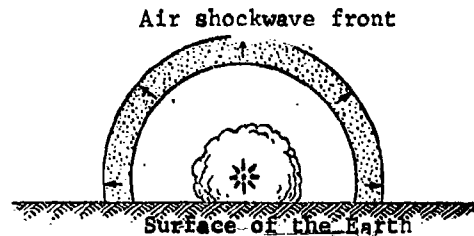
Fig. 17. Air shockwave during ground explosion.

Let us consider the distribution of the air pressure in the wave in greater detail. To measure this pressure we have to arrange special instruments along the ground surface. Fig. 18 shows a simplified diagram of one of these instruments, which are known as pressure recorders. The instrument is set flush with the ground. The shockwave glides over the surface of the instrument, the air pressure acts on a diaphragm and bends it. A lever attached to the diaphragm is turned and a recording pen at the end of it registers the shift on a revolving drum. Since the air pressure changes with time as the shockwave moves across the instrument, a graph showing the variation in pressure is automatically recorded on the drum. The graph is shown in Fig. 19. Time is plotted along the horizontal axis and pressure along the vertical axis. At first we see a horizontal line on the left hand side of the graph showing the normal atmospheric pressure. Then we find a sharp jump in pressure at the moment the front of the air shockwave impinges upon the diaphragm. At this moment the air pressure increases in jumps from the normal (atmospheric) to the maximum pressure in the wave, right behind the front. The difference between the maximum pressure and the atmospheric pressure is called the/pressure _OVER_ at the

front of the wave.
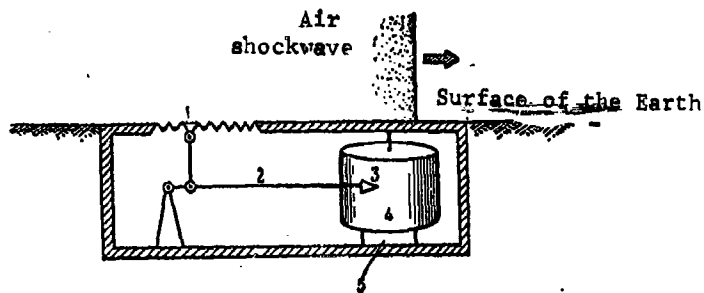
Fig. 18. Diagramatic cross-section of a pressure recorder: 1) diaphragm sensing
air pressure in shockwaves; 2) lever turning when diaphragm is depressed
by air pressure; 3) recording pen at end of lever; 4) drum on which air
pressure is recorded; 5) electric motors revolving drum.
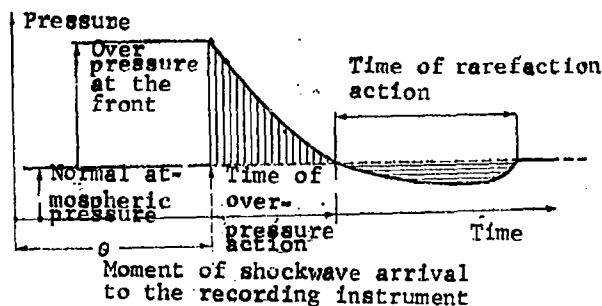
Fig. 19. Variation in pressure in air shockwave recorded by recording instrument
as function of time.

After the wave front has passed, the air pressure gradually begins to fall,
reaches normal atmospheric pressure and then drops still lower. This means that
a layer of rarefied air follows the compressed air in the shockwave. The rarefied
layer is very thick and the REDUCED pressure lasts for some time. Then the
pressure rises to normal. This means that the shockwave has passed.

-64-

1) Normal pressure;
2) Compression zone ;
3) Rarefaction zone
4) Normal pressure
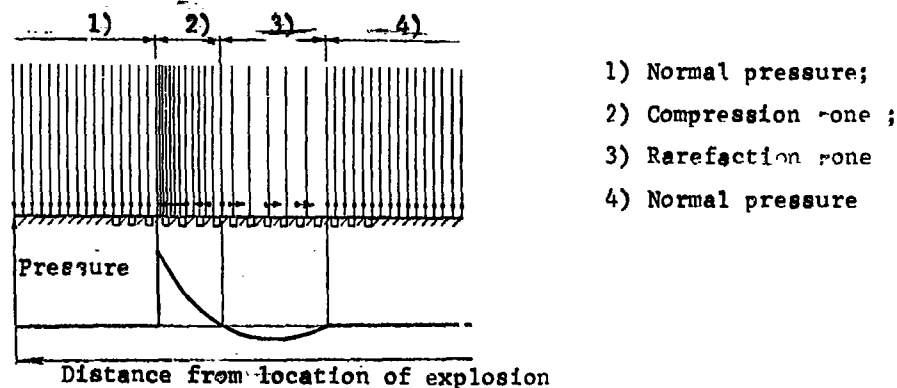
Fig. 20. Pressure distribution through air shockwave.

We have considered pressure variation in the air at a certain point during the passage of a shockwave. Now let us see how the pressure is distributed in the wave at a certain moment in time. To do this let us ascertain what a WHOLE number of instruments ALL arranged in the direction of the wave's motion would show.

Fig. 20 illustrates this momentary distribution of pressure. The density of the vertical hatching is used to represent the density distribution in the air trapped by the shockwave at a given moment. It is clear that the greater the pressure, the greater the density of the air.

The increase in density in the compression zone is due to the shift of a certain amount of air from the rarefaction zone, where the density of the air is correspondingly reduced.

The movement of the air behind the shockwave front occurs at a set velocity. Its motion FOLLOWS the same direction as the wave. But the velocity of the front, as already pointed out, is much greater than the velocity of the air just behind the front.

As the wave front moves away, the velocity of the air at the point we are considering is reduced, then becomes zero, and finally the movement of the air changes direction. The air begins to move in the opposite direction to the wave. Fig. 20 shows arrows, the size and direction of which indicate the described motion of the air.

Thus, the following things happen when an air shockwave passes by. The moment the shockwave front reaches a certain point, the pressure is increased to maximum virtually instantaneously. There is a simultaneous increase in the density of the air. Since gases always heat up when rapidly compressed, the temperature of the air also is raised. The hot, densified air moves in the direction of the wave. It is as though there were a sudden gust of very strong and hot wind lasting about a second. Then the pressure drops below atmospheric, the direction of the wind REVERSED the air becomes rarefied and is cooled below normal. In damp weather the cooling of the air may result in a momentary mist in the rarefaction zone. If the explosion is observed from afar in such weather, it is possible to see a rapidly expanding ball of mist - this is the rarefaction zone following the invisible compression zone.

If a fairly strong shockwave reaches the moisture-saturated higher layers of the atmosphere, the formation of a rapidly expanding ring of clouds can be observed.

In the right conditions the compression zone is also visible. For example, if we stand on a hill and look at a meadow or field along which the airwave is moving, we can see how it bends and flattens the grass and ANY other vegetation as it goes. In dry weather we can see the shockwave raising clouds of dust. ROCKETS leaving smoke trails have often been used abroad to study nuclear explosions. These missiles are launched just before the nuclear explosion and the smoke trails make it possible to see how the air set in motion by the shockwave is shifted about and compressed. Diagramatic representation of this is shown in Fig. 21.

The time over which the air shockwave (pressure OVER acts is usually so considerable that the basic destruction which it might cause occurs long before the arrival of the rarefaction zone; in practice, in order to assess the destructive effect we need only know the OVER PRESSURE on which the velocity of motion of the air in the compression zone depends, and the pressure which this air exerts on

-66-

objects it encounters. Hence the/pressure . . at the front is the most important

quantitative characteristic of the air shockwave and needs very thorough investi-

gation.

Reactive-missiles leaving smoke trails

Shockwave front

Compression zone

Rarefaction zone

Surface of the Earth
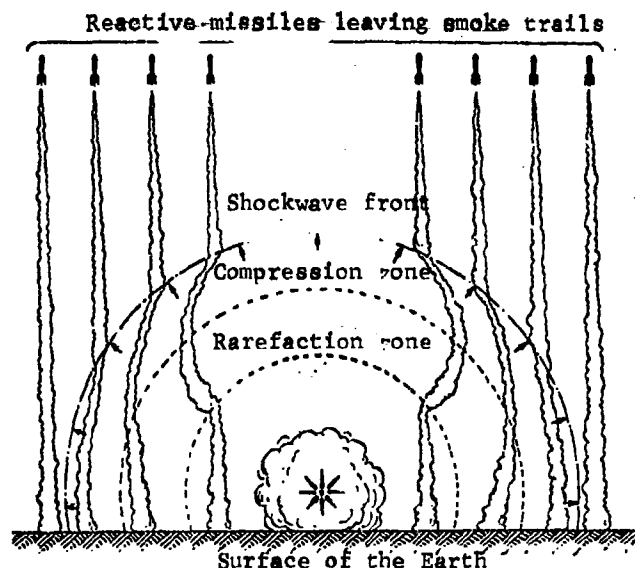
Fig. 21. Diagramatic representation of the distortion of smoke trails left

by special rockets during spread of air shockwave.

3. Determining the parameters of an air shockwave

TNT equivalent. THE different effect of any explosion, including the nuclear

one, depends mainly on the energy released. Hence, to calculate quantities deter-

mining the effect of an explosion, we must know its energy. As is well known,

energy is usually expressed in kilogram meters, kilowatt hours and other units. In

the case of a nuclear explosion, however, it is conventional to use another method

of measuring energy. For a clear estimation of the effect of a nuclear explosion ,

we compare it with the explosion of conventional explosive. Hence the energy

released during a nuclear explosion is determined in the following way. We select

the amount of conventional explosive which releases the same amount of energy as

the given nuclear charge when exploded. The weight of this conventional charge is

what characterizes the energy of the nuclear explosion.

-67-

One of the commonest explosives which has been studied in great detail is TNT. Other explosions are therefore described by the TNT equivalent. The TNT equivalent is the weight of a charge of trinitrotoluene producing the same amount of energy as is obtained during the explosion of a corresponding nuclear charge.

The TNT equivalent is expressed in kilograms, tons or kilotons (1 kiloton equals 1000 tons) or, if the charge is very large, in megatons (1 megaton = 1 million tons).

Most of the energy from the explosion of conventional explosive is manifested as a mechanical effect, and in particular, goes to form the air shockwave.   is not the case during a nuclear explosion. As has already been pointed out, an appreciable amount of energy in a nuclear explosion is carried a considerable distance by different types of radiation (Luminous/penetrating radiation). Hence only about 35% of the total energy is used to form the shockwave.

The total energy of a nuclear explosion is expressed in terms of total TNT equivalent.

The energy determining the effect of the air shockwave is expressed in terms of the shockwave TNT equivalent.

The principal expression for the nuclear energy used to assess the mechanical destructive effect and for calculations relating to shockwaves is the shockwave TNT equivalent.

This quantity is usually determined experimentally on the basis of measurements of the over/pressure   at the front of the air shockwave at different distances from the point of the explosion.

If it is necessary to determine the TNT equivalent in conventional energy units, we have to take it into account that an equivalent of 1 kg corresponds to approximately 430,000 kilograms of work. In otherwords, the explosion energy from 1 kg of TNT is sufficient to raise a load weighing 1 kg for a height of 430,000 meters, or 430 km.

It follows from this that a nuclear explosion with a TNT equivalent of 10,000 tons, given total utilization of its mechanizal work, could hurl a heavy cruiser weighing 10,000 tons to a height of 430 km, as well.. Hence the energy is

quite high!

Law of similarity. As a whole, the regularities governing the development of an explosion and its different effects are rather complicated and varied. There is, however, a very simple and tested method of solving many problems in the sphere of the explosion, which makes it much easier to calculate the/pressure of the wave, the destructive range and many other factors. This method is based on the law of similarity.

According to this law, the distance between the point of explosion and a point with preset properties on the air shockwave front is proportional to the cubic root of the TNT equivalent.

Let us illustrate this with an example. It is known from both theory and experiment that when a charge with an air shockwave TNT equivalent of q_A = 10,000 tons is exploded, a pressure head of 10 kg per square cm at the front is observed at a distance R_A = 220 m.

We can ask at what distance R_B we observe exactly the same/pressure at the shockwave front during the explosion of a charge with a shockwave TNT equivalent of q_B = 10 megatons?

The task can most easily be solved in the following way. In the given case the TNT equivalent is stepped up a thousand times. This is clear from the relationship

$$\frac{q_B}{q_A} = \frac{10\,000\,000}{10\,000} = 1000.$$

If the TNT equivalent is a thousand times greater, the distance over which the same pressure is observed must be increased $\sqrt[3]{1000}$ = 10 times. Hence, given a TNT equivalent equal to 10 megatons, the/pressure at the front of 10 kg per square cm is observed at a distance of R_B, greater than R_A by a factor of 10. It follows from this that

$$R_B = R_A \sqrt[3]{1000} = 10 R_A.$$

Taking the above value of R_A into account, we find that

$$R_B = 2200 \ m = 2,2 \ km$$

On the basis of this example, we can note down the following general equations

$$\frac{R_A}{R_B} = \sqrt[3]{\frac{q_A}{q_B}} \quad \& \quad \left(\frac{R_A}{R_B}\right)^3 = \frac{q_A}{q_B}.$$

If we divide the TNT equivalent by the cube of the corresponding distance, we find a constant. We can write down (provided the wave front parameters are constant)

$$\frac{q_A}{R_A^3} = \frac{q_B}{R_B^3} = \frac{q}{R^3} = \text{constant}$$

For example, for a pressure head of 10 kg/cm^2

$$\frac{q_A}{R_A^3} = \frac{q_B}{R_B^3} = 0,00095 \quad t/m^3$$

If we express q_A and q_B in kilograms, we get another quantity, which is also constant

$$\frac{q_A}{R_A^3} = \frac{q_B}{R_B^3} = 0,95 \quad kg/m^3$$

Thus, for every given value of the/pressure over at the shockwave front there is a definite relationship q/R^3.

This means that on the basis of experiment or theoretical calculation we can determine the relationship for any one value q and then use it to calculate it for other TNT equivalents.

This is extremely convenient from the practical point of view, since we can then experiment with small charges or ordinary TNT and apply the results obtained to the pressure head of the air shockwave from as powerful a nuclear explosion as we wish, and know for certain that the theoretical and experimental values will tally, provided we know the corresponding TNT equivalents beforehand.

So that the experimental data can be more easily applied in practice, we select a suitable equation which gives us the relationship between the pressure head and the ratio q/R^3.

The/pressure over at the shockwave front is usually designated Δp_f. Here Δ means that we are not dealing with the total pressure, but the over pressure

(the pressure in excess of the atmospheric). The subscript f means that we are dealing with the OVER PRESSURE at the front of the wave.

-70-

The simplest and most suitable equation in practice for rough calculations of $\Delta \underline{p}_f$, provided it lies approximately between 0.1 and 2 kg/cm², is the following

$$\Delta p_\phi = 3,9 \sqrt{\frac{q}{R^3}}.$$

Here $\Delta \rho_f$ is obtained in the kg/cm² when $\underline{q}$ is expressed in kolograms and $\underline{R}$ in meters.

This equation is a very simple expression of the relationship between $\Delta \underline{p}_f$ and $\underline{q}/\underline{R}^3$, resulting from the above-considered law of similarity.

Calculation of overpressure at air shockwave front. This method of calculating the overpressure of an air shockwave is approximate. The given equations are suitable only when the overpressure derived on the basis of them ranges between 0.1 and 2 kg/cm². In practice we often need to go further. Hence the need arises to extend and make more accurate the calculation methods.

Electronic computers have been used to determine the overpressure at the Aberdeen Testing Range in the USA[1].

The results can be expressed as tables or graphs which plot the different conditions for the explosion.

It is very important to select the most convenient unit for measuring the distance between the explosion point and the point at which the overpressure is to be determined. The unit of distance should be chosen in such a way as to obtain the same graphs for all TNT equivalents. Furthermore, we have to make allowance as well for the original atmospheric pressure. The explosion may occur at different heights above the locality, at different heights in the mountains and also in different kinds of weather, when the air pressure varies. Consequently, the original air pressure may effect the results of the calculation.

To cope with this problem, we have to keep in mind that the air pressure is proportional to the energy contained in each cubic meter of air. This energy is the energy of motion of the air molecules.

1)
Journal of Applied Physics, 1955, June, Vol. 26. No. 6, p. 766.

If the shockwave has spread from the site of the explosion to the point R, the total volume of air which has undergone the effect of the explosion by this time is equal to

$$\frac{4}{3}\pi \cdot R^3,$$

The energy initially contained in this volume is proportional to

$$\frac{4}{3}\pi R^3 \cdot P_0,$$

where P_0 is the initial atmospheric pressure. The quantity $\frac{4}{3}\cdot\pi$ is the same in all cases. Thus, it can be assumed that the energy contained prior to explosion in the air which has been acted on by the shockwave is proportional to the product $R^3 \cdot P_0$.

The energy supplied to the air during the explosion is proportional to the TNT equivalent for the shockwave q.

Theory and calculations show that the overpressure is only a function of the relationship between the explosion energy producing the shockwave and the energy present beforehand in the medium in which the wave occurs. Thus, the over-pressure depends only on the quantity

$$\frac{q}{R^3 P_0} = k.$$

Hence,

$$R = \sqrt[3]{\frac{q}{kP_0}} = \sqrt[3]{\frac{1}{k}}\,\sqrt[3]{\frac{q}{P_0}}.$$

Let us designate the quantity

$$\sqrt[3]{\frac{1}{k}} = R_1.$$

Thus, we can write down

$$R = R_1 \sqrt[3]{\frac{q}{P_0}}$$

and

$$R_1 = \frac{R}{\sqrt[3]{\frac{q}{P_0}}}.$$

-72-

It may be assumed that when $\underline{k}$ has a certain value, $\underline{R}_1$ also has a corresponding certain value.

Since the overpressure at the shockwave front, as stated above, is only a function of $\underline{k}$, it also depends on the corresponding value of $\underline{R}_1$, which can be termed the referred distance.

To arrive at this referred distance $\underline{R}_1$, we have to divide the true distance $\underline{R}$ by

$$\sqrt[3]{\frac{q}{P_0}} = r.$$

r is the referred unit of length. Expressing the difference between the point of the explosion and the point at which we are determining the overpressure Δp_f at the shockwave front in these units, we can derive the same values of Δp_f for all possible initial pressures in the medium $\underline{P}_0$ and the shockwave TNT equivalent.

If we then have to go back again from $\underline{R}_1$ to $\underline{R}$, we need only multiply $\underline{R}_1$ by $\underline{r}$ and we get $\underline{R}$ in the right unit. In practical calculations it is best to express $\underline{q}$ in tons and $\underline{P}_0$ in kg/cm^2.

Normal atmospheric pressure can be considered to be 1 kg/cm^2 with fair accuracy. Under these conditions we can adopt the following simple formula

$$r = \sqrt[3]{q}.$$

The overpressure should also be measured in relative units on the basis of the ratio

$$\frac{\Delta p_\Phi}{P_0}.$$

Figs. 22 and 23 show graphs enabling us to find Δp_f for set $\underline{R}$, $\underline{P}_0$ and $\underline{q}$ under the circumstances described.

The solid curve in these graphs represents the variation in $(\Delta p_f)/\underline{P}_0$ due to $\underline{R}_1$.

These graphs (provided c_v/c_v is constant) constitute analytical solutions, arrived at with electric computers, of the problem of the propagation of spherical shockwaves in unlimited atmosphere.

-73-
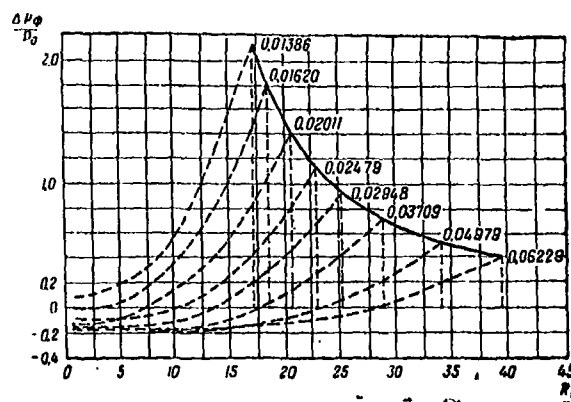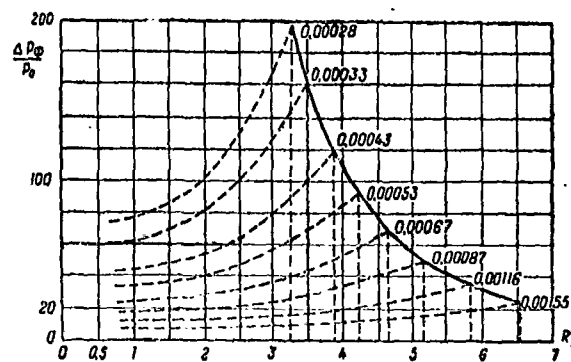
Fig. 22. Graph showing parameters of shockwave. The corresponding values of τ_0 are shown alongside some of the points on the curve.
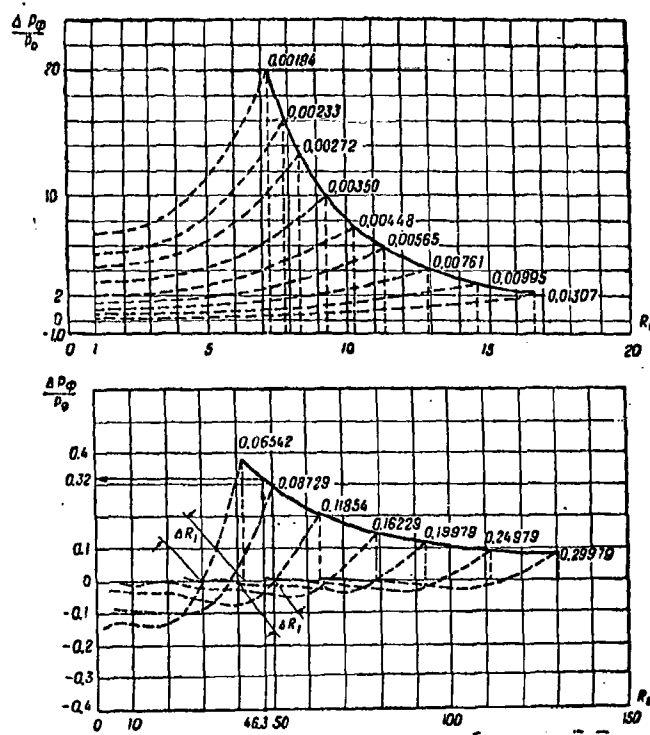
Fig. 23. Graph showing the parameters of a shockwave. The corresponding values of τ_0 are shown alongside certain points on the curve.

In order to apply the graphs given above, we must first determine the value

$$r = \sqrt[3]{\frac{q}{P_0}}.$$

Here q is expressed in tons and P_0 in atmospheres. After that we have to find the referred distance

$$R_1 = \frac{R}{r},$$

Having found R_1 on the horizontal axis, we find the ratio

$$\frac{\Delta p_\phi}{P_0}$$

on the scale along the vertical axis.

Multiplying this by P_0, we get Δp_f . If $P_0 = 1$ atm, the operation is simplified; here

$$r = \sqrt[3]{q} \text{ (q in tons)}$$

and

$$\frac{\Delta p_\phi}{P_0} = \Delta p_\phi \ (\Delta p_\phi \text{ и } P_0 \text{ in atmospheres or kg/cm}^2)$$

Let us illustrate this method of calculation with an example. Let us assume we have a nuclear bomb with a total TNT equivalent of 20,000 tons. In this case the shockwave TNT equivalent is $q = 10,000$ tons. Let us determine Δp_f during the explosion of this bomb, if $P_0 = 1$ kg/cm^2 = 1 atm at a distance $R = 1000\ m_\omega$ To do this we first determine r

$$r = \sqrt[3]{\frac{q}{P_0}} = \sqrt[3]{\frac{10\,000}{1}} = 21.6 \text{ m}$$

Now we find the referred distance. It is

$$R_1 = \frac{R}{r} = \frac{1000}{21.6} = 46.3.$$

Now we use the graph in Fig. 23 (the solution is shown by arrows) on the basis of $R_1 = 46.3$ to find the following: $\frac{\Delta p_\phi}{P_0} = \Delta p_\phi = 0.32$ атм $= 0.32$ kg/cm^2

Calculating the propagation time of the air shockwave and the size of the compression zone using graphs. Besides calculation of the overpressure by means of the above-mentioned graphs, we can also use this method to determine the time taken for the shockwave to spread θ. Theory shows us that this time is proportional to

the above-mentioned value $\underline{r}$

$$\theta = \tau_0 r = \tau_0 \sqrt[3]{\frac{q}{P_0}} \; \text{sec}$$

Here, as before, $\underline{q}$ is expressed in tons and $\underline{P}_0$ in atmospheres or kilograms per square centimeter; τ_0 is the proportionality factor.

The corresponding values of τ_0 are shown next to some of the points on the curve in ^{F}igs. 22 and 23.

In relation to the example considered above, in which $\underline{q} = 10,000$ tons, $\underline{R}$ = 1000 m and $\underline{r} = 21.6$ m, we can take it approximately from the graph in Fig. 23 that $\tau_0 = 0.075$.

Consequently, the time taken by the shockwave to arrive at $\underline{R} = 1000$ m is

$$\theta = \tau_0 \cdot r = 0,075 \cdot 21,6 = 1,6 \; \text{sec}$$

Figs. 22 and 23 also show, apart from the curves drawn in thick lines, a series of broken curves ɪɴᴅɪᴄᴀᴛɪɴɢhow the pressure is distributed in an air shockwave behind the front in the air located between the point of explosion and the wave front.

For example, the width of the compression zone in the above example, as is clear from ^{F}ig. 23, can be determined as the mean of two positions of the wave. One of them is approximately

and the other

$$R_1^* = 42$$
$$R_1^{**} = 50.$$

The depth of the wave in both cases is approximately

$$\Delta R_1 = 13.$$

The true depth of the compression zone is

$$\Delta R = \Delta R_1 r = 13 \cdot 21,6 = 281 \; \text{m}$$

The rarefaction zone stretches in this case as far as the actual point of the explosion, as is clear from ^{F}ig. 23.

Calculating the air velocity behind the shockwave front. The velocity of the air behind the shockwave front according to the theory is

$$U_\phi = 10\,000\ \frac{\Delta p_\phi}{\rho D}\ \text{m/sec}$$

Here Δp_f is the overpressure in atmospheres or kg/cm^2;

ρ is the air density in the atmosphere;

D is the velocity of the shockwave front in m/sec.

The quantity ρ can be determined from the equation

$$\rho = 0.125\, P_0\ \frac{1}{1 + \frac{t}{273}}\ \text{kg} \cdot \text{sec}^{2}/\text{m}^4$$

Here P_0 is the pressure of the atmosphere in atmospheres or kg/cm^2.

As can be seen from the equation, the effect of temperature on the air density is insignificant for practical purposes. Taking this into account, we can write down on the basis of the two last equations

$$U_\phi = 80\,000\ \frac{\Delta p_\phi}{P_0 \cdot D}.$$

$\Delta p_f / P_0$ can be found by the above described method from the graphs in Figs. 23 and 22. D can be found from the equation

$$D = c\ \sqrt{1 + 0.86\ \frac{\Delta p_\phi}{P_0}}.$$

Here c is the speed of sound, which is $c = 20\sqrt{T}$;

T is the temperature in $^\circ\text{K}$.

4. Interaction between shockwaves and obstacles in their way.

Regular reflection of shockwaves from stationary obstacles in their way.
Very often an air shockwave acts under conditions where it encounters some sort of obstacle in its path. The moving masses of air are slowed down by the obstacle and the pressure, temperature and density of the air are further increased. This results in a greater destructive effect on the part of the shockwave than for a wave able to GLIDE PAST obstacles.

The increase in the pressure of a shockwave encountering an obstacle is greatest when the latter is perpendicular to the direction of motion of the wave. In this case the velocity of motion of the air behind the front of the oncoming wave is totally damped and the air by the obstacle is compressed to the greatest extent, which indeed explains the mentioned increase in pressure, temperature and

-78-

density.

About 50 years ago the well-known Russian scientist Zhukovskiy drew
attention to the certain similarity between waves spreading over the water surface
and air shockwaves. All those who have observed the motion of sea or river waves
near the vertical wall of an embankment or near a steep bank know well that when the
wave runs against the steep wall and strikes against it, there is a large splash
which lifts some of the moving water considerably higher than the original crest of
the wave. It is clear that the water is only thrown upwards because the pressure
is sharply increased when the water wave strikes the obstacle. This is in some
respects similar to the phenomena observed when an air shockwave encounters an
obstacle.

The moment the shockwave front meets the plane of the obstacle, the surface
of the latter is suddenly subjected to A pressure composed, as it were, of two
parts: the pressure AT which the air was compressed at the density jump and the
pressure due to the virtually instantaneous halting of a moving mass of air (vel-
ocity head pressure). The velocity head pressure substantially exceeds the static
pressure (possessed by the air on the crest of the wave). Hence the total pressure,
too, may be much greater than the static pressure. The maximum pressure on the
obstacle occurs AT the first moment of impact, since it is at this moment that the
velocity of the medium on the crest and the static pressure are highest.

At the first moment of impact, it is only the particles which are at the
front of the effective wave which are stopped; then come the particles which are
contained in the next layer and so on. Consequently, there is a new jump in den-
sity at which the motion of the air in the direction of the moving wave is ceased,
and there appears a new shockwave - a reflected one moving in the opposite direction,
that is to say a wave from the obstacle.

The reflected wave front gradually moves away from the obstacle. At first
this motion is due mainly to the stopping of the air in the effective wave. This is
similar to what is observed when a locomotive pulling a freight train at a slow
speed is suddenly stopped. In this case the car closest to the locomotive is the

first to stop, while the remainder continue moving by inertia. Then the second car stops, after it the third, and so on, until the wave of braking reaches the last car.

The over pressure occurring during direct impact between the air shockwave and the obstacle can be calculated by the equation

$$\Delta p_{ref} = 2\Delta p_\phi + \frac{6\Delta p_\phi^2}{\Delta p_\phi + 7 P_0},$$

where Δp_f is the overpressure at the front of the forward (incident) wave;

P_0 is the atmospheric pressure;

Δp_{ref} is the overpressure at the reflected wave front.

According to Δp_f, the increase in pressure during reflection may differ. For example, if Δp_f is many times greater than atmospheric pressure, which is 1 kg/cm^2, we find

$$\Delta p_{ref} = 8\Delta p_\phi.$$

This means that when very strong shockwaves are reflected from obstacles, the pressure is increased by a factor of eight. (It may even (increased) in practice to eleven times if the shockwaves are very strong).

Conversely, if Δp_f is equal to atmospheric pressure, $\Delta p_{ref} = 2.75$, that is to say, there is only an increase of 2.75 times.

Table 2 gives the values of Δp_{ref} for different Δp_f.

Table 2.

Overpressures at the front of the reflected wave Δp_{ref} for different values of the overpressure Δp_f in an air shockwave striking an obstacle perpendicularly (at an atmospheric pressure of 1 kg/cm^2)

Δp_f (kg/cm^2)	0,05	0,1	0,3	0,5	1	2	3
Δp_{ref} (kg/cm^2)	0,10	0,21	0,65	1,20	2,76	6,67	11,2
$\Delta p_{ref}/\Delta p_f$	2,0	2,1	2,2	2,4	2,8	3,3	3,7

It is clear from the table that in cases of practical importance, when Δp_f ranges approximately between 0.05 and 3 kg/cm^2, the increase in maximum overpressure through reflection ranges from 2 to 3.7.

As soon as the air has been slowed down by the obstacle, it begins to move in the opposite direction. Here the energy spent on compressing the air is reconverted into energy of motion to a considerable extent, and at some distance from the obstacle there occurs a reflected shockwave similar to the wave proceeding directly from the charge, though slightly weakened by energy losses during reflection. If the obstacle is flat and the wave is reflected from it during the explosion of a concentrated charge at a distance H from the obstacle, then as can be seen from Fig. 24, the reflected wave will spread just as though there were a charge reducing the wave by an explosion behind the obstacle, also at a distance H. This reflection is termed regular and is similar to the reflection of sound, light and water waves from various obstacles.

Irregular reflection of shockwaves. Deviation from regular reflection is already present to some extent from the beginning and is indicated by certain features in the motion of the reflected wave. The point is that the reflected wave moves partly through air which has been heated up and densified by the incident wave (Fig. 25), on account of which the velocity of propagation of the reflected wave is increased.

As long as the angle α between the incident wave front and the reflecting surface is less than 45° (at close distances from the epicenter of the explosion), the reflection shown in Fig. 25 is maintained. But when this angle becomes greater than 45° (at greater distances from the epicenter), the layer of air

-81-
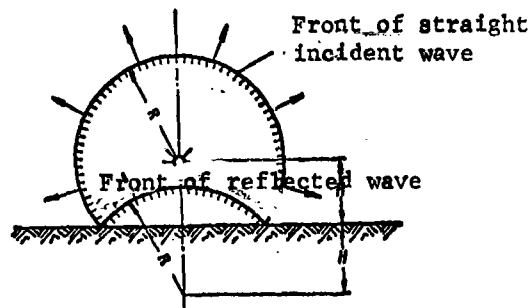
Fig. 24. Diagram of regular reflection of shockwave by earth surface.

densified during reflection forces back the incident wave and moves forward, over-
taking it. This effect - irregular reflection - is shown in Fig. 26. A similar
phenomenon can often be observed in nature. For example, when a stream of water
flows along the gutter, we often observe that a wave produced by a stone or some
other obstacle strikes the edge of the sidewalk and is reflected by it. If the
stream is fairly strong and moving fairly fast, there is irregular reflection of
the wave by the edge of the sidewalk.
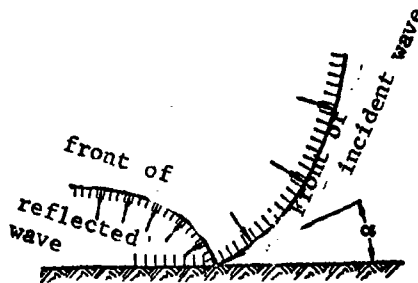
Fig. 25. Propagation of incident and reflected waves.

During reflection, the pressure is increased. If the angle α between the wavefront and the reflecting surface is zero, the increase in pressure proceeds as might be expected from the equation given above for $\Delta p_{\sim ref}$. If the angle is 90°, there is no reflection at all and the pressure at the wavefront is unchanged. But if the angle α varies between 0 and 90°, the greatest increase in pressure is found during the transition from the regular to the irregular reflection.
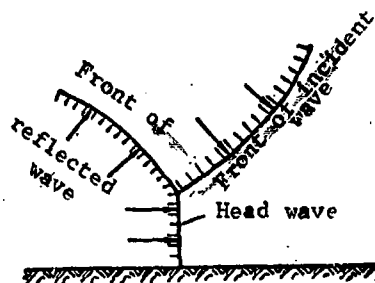
Fig. 26. Irregular reflection of shockwave.

Fig. 27 is a graph showing how many times the overpressure of the reflection $\Delta p_{\sim ref}$ increases at different values of the angle α.

Each of the curves in Fig. 27 represents a specific overpressure $\Delta p_{\sim f}$ in the wave approaching the obstacle. The values of $\Delta p_{\sim f}$ are placed beside each curve.

It follows from the graph in Fig. 27 that the greatest pressure increase is found during the change from regular to irregular reflection for angles ranging between 40 and 70° (depending on the overpressure at the incident wavefront).

The wave formed when the incident and reflected waves merge is called the head wave (Fig. 26). The front of this wave is perpendicular to the reflecting surface. The overpressure at the front of the head wave is approximately equal to the overpressure $F \circ R$ perpendicular incidence of the shockwave on the obstacle. This is valid if the angle between the incident wave front and the reflecting surface is only slightly greater than 45°. Should the angle be greater, the head

1)
This graph is taken from the book "The Effects of Atomic Weapons", New York, London, 1950.

-83-
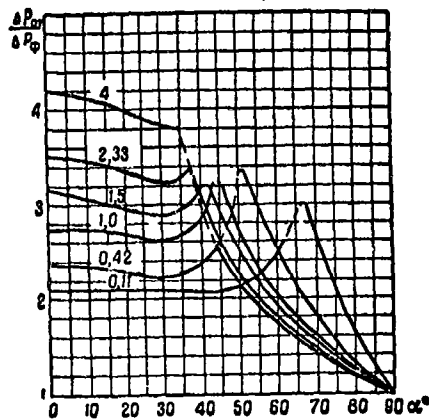
Fig. 27. Graph showing ratio of overpressure in reflected (or head) wave and overpressure in incident wave $\dfrac{\Delta \rho_{ref}}{\Delta \rho_f}$ as function of angle α between incident wavefront and obstacle.

wave is higher and its overpressure slowly begins approaching the pressure at the incident wave front. When the angle approaches a right angle, the overpressure at the head wave front is only slightly in excess of the overpressure of the incident wave.

Let us now consider the propagation of shockwaves during the explosion of a charge some way above the flat surface of the earth. As is known, this is called an air explosion.

Fig. 28 shows the development of the reflection of the air shockwave from the surface of the earth.
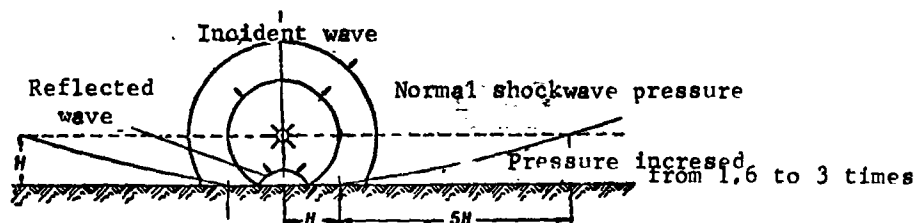
Fig. 28. Formation and propagation of reflected shockwave during air nuclear explosion.

At   distances from the epicenter LESS than the height H of

the point of explosion above the ground, there is a regular reflection, while at

points whose distance from the epicenter R is greater than the height H, an

irregular reflection begins and a head wave is produced. The height of the front

of this wave keeps increasing. The front eventually attains the height at which

the explosion occurred. After this the shape of the front begins to change and

it becomes like part of the surface of a sphere with its center at the epicenter.

Flow of shockwaves around objects of finite dimensions. The motion

of an air shockwave over smooth and even ground is a comparatively rare case. It

is much more likely THAT the shockwave WILL encounter buildings, trees, various

irregularities in the terrain and other local objects. In such cases the prop-

agation of the air shockwave changes. It is partly reflected from local objects

and partly flows round them.

Let us trace this effect in a very simple example. Let us imagine that

we have a fairly strong vertical wall which withstands the effect of an air shock-

wave. Under these conditions the oncoming wave is reflected from the wall. Let

us assume the wave strikes the wall perpendicularly. This moment is shown

diagramatically in Fig. 29a. As a result of reflection, a layer of densified air

bounded on the outside by the front of the embryonic reflected wave is formed

close to the surface of the wall.

Attention must be given to the fact that at this moment their

begins a certain distortion of the plane front at the edge of the obstacle in the

densified air layer behind the reflected wave front. The distortion means that

the strongly compressed layer of air at the surface of the wall has no support

below it, where the air pressure is lower. As a result the air from the densified

layer begins to travel upwards and a rarefied wave (wave of reduced pressure)

begins to spread down the densified layer. Within   the wave the air

moves both in an upward direction and is also deflected in the direction of the

principal shockwave by the air moving over the obstacle. The direction of motion

-85-

of the air is thereby curved and we find an eddy twirling in a clockwise

direction, as shown in Fig. 29a. The occurrence of the eddy sharply reduces the

air pressure on the top of the wall, since, first, there is a reduction in the

air density through its spreading out, and second, centrifugal force presses the

air away from the upper surface of the obstacle. On the outside the eddy is

bounded by the curved front of the reflected shockwave. Here centrifugal force

densifies the air behind the reflected wave front and the pressure becomes greater

than in the part of the wave adjoining the obstacle. It is just this which

explains the occurrence of the curved area of the reflected shockwave encompassing

the top of the obstacle.

As time passes these effects become more complicated and develop, but

their overall nature remains the same. Fig. 29b shows the moment that the curved

area of the reflected wave rounds the top edge of the obstacle and moves down the

other side, merging with the front of the original wave.

As a result the rear surface of the obstacle is gradually subjected to

increased air pressure while/the front surface which faces the explosion the load

is gradually removed. The rarefied wave moves down the front of the obstacle and

gradually reduces the high pressure produced by reflection of the wave from the

obstacle. But this reduced pressure, however, is rather higher than the pressure

on the other side of the wall.

Then comes the next stage in the flow around the obstacle. The wave

(eddy) reaches the ground and begins to be reflected by it with a corresponding

increase in pressure, just as the primary shockwave from the explosion is

reflected from the ground. This stage in the process is shown in Fig. 29c.

As it moves further the wave flowing round the obstacle reaches the

ground forming ever greater angles with the latter. The center of curvature of

the front of this wave is   approximately DOUBLE THE/of the obstacle.

Under these conditions, at a distance equal to twice the height 2H of the

obstacle, the shockwave front rounding the obstacle forms an angle of about 45°

with the ground, leading to the formation of the head wave (Fig. 30). As the
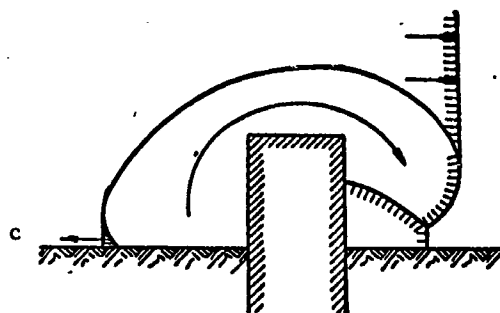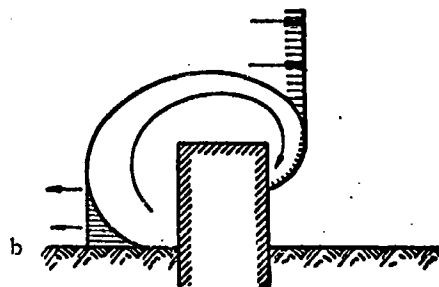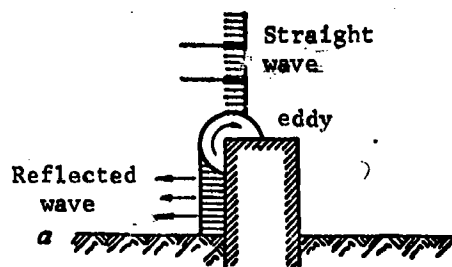
Fig. 29. Flow of shockwave around obstacle: diagrams a, b and c show reflection
of the shockwave by a vertical wall and development of flow around it.

wave moves further on, an irregular reflection zone is formed behind the obstacle, in which the effect of the overpressure is sharply increased. The head wave formed during the process carries on travelling. The eddy formed when the shockwave flows round the edge of the obstacle becomes detached from it and moves on together with the mass of air.
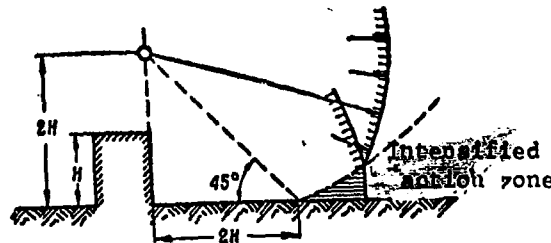
Fig. 30. Formation of head wave and intensified action zone behind the

obstacle.

Let us now consider flow around a high, but narrow wall. The same effects are observed at each edge of the wall as were discussed before. They are shown in the series of diagrams in Fig. 31. A specific feature of this case, as compared with the previous one is the fact that the waves rounding the obstacle on different sides run into each other. They collide and are reflected from one another. The reflection occurs in the same way as if behind the middle of the obstacle there was a thin, though strong obstacle reflecting the waves at the points of collision, just as they were reflected in the previous example by the ground. The result is a region of irregular reflection with increased effect

at a distance from the obstacle approximately equal to its width. This can be seen from the last diagram in Fig. 31.
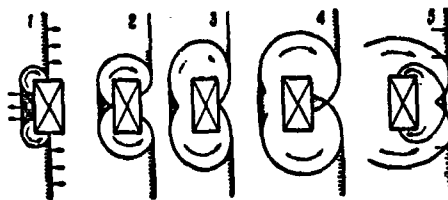
Fig. 31. Stages in flow around obstacle by shockwave (from above).

We can consider yet another case in which the wave flows round an obstacle of finite height and width. Here there is flow over the top as well as around the sides. The result is that the waves come together from all three sides at the same time in the irregular reflection zone and the intensification of the explosion effect is so strong that the overpressure of the shockwave not only reaches the level of the overpressure of the shockwave prior to impact against the obstacle, but considerably exceeds it. In this case the destructive effect of the explosion over a certain area behind the obstacle is greater than if there were no barrier at all.

Expansion of the heightened and reduced pressure regions when the shockwave flows round an obstacle the height of which is equal to half its width is shown in Fig. 32 from above. It is important to point out here that the greatest reduction in the explosion effect is not found in the middle of the area protected by the obstacle from the effect of the wave, but on either side of a line through the center. This fact is rather unexpected, although it is found to be very much the case. It always has to be taken into account when using local objects for protection from an atomic explosion.

Let us now go on to consider the forces acting as a whole on an obstacle which is subjected to the shockwave load. If the obstacle were very large in size, compared with the depth of the compressed air zone, the overall force on the obstacle would be due to multiplication of the overpressure by the area of the obstacle subjected to the pressure.
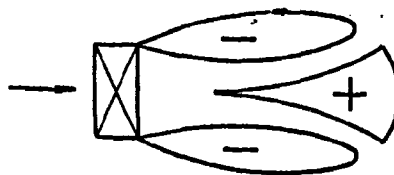
Fig. 32. Zones of reduced (minus) and increased (plus) effect caused by the air shockwave behind the obstacle.

If the obstacle is small compared with the depth of the shockwave, it begins to flow round the former, as we saw above. It then changes to the steady-state flow by a stream of air around an obstacle, as is observed, for example, during a fairly strong wind under normal circumstances. The transition state lasts for enough time for the rarefied wave and the vortical motion to completely encompass the obstacle. The time t_1 can be calculated approximately in the following way

$$t_1 = \frac{B}{340} \text{ sec}$$

Here B is the width of the obstacle in meters. If t_1 is small compared with the time over which the overpressure τ acts, it may be assumed that the effect of the air shockwave is similar to that of a hurricane with the greatest wind velocity U_5.

It may be roughly assumed that this flow occurs whenever t_1 is ten or more times shorter than τ. We can use this to find the width of an obstacle on which the effect of the shockwave approaches that of a gust of wind.

If, for example, $q = 15$ million kg and $R = 100$ m, then $B \leqslant 22$ m.

This holds for a case often encountered in practice in which the natural oscillation period of the obstacle hit by the shockwave exceeds the time taken by the wave to flow round it t_1.

Thus, medium sized houses $(B \leqslant 22$ m) and especially such objects as factory stacks, steel bridges, pilons, telegraph poles and so on, stand up to the shockwave from a powerful explosion in much the same way as to a sudden hurricane.

5. The effect of topography on the air shockwave

Let us consider how the air shockwave behaves when it hits a slanting obstacle, for example, the side of a hill facing the explosion. Let us assume the angle between the shockwave front and the side of the hill is greater than 45°. This means that we have the conditions under which there is irregular reflection of the wave. Fig. 33 shows some of the successive positions of the wave hitting the front side of the hill. There is a clearly defined region of irregular reflection near the surface, and a head wave with a pressure greater

than the original wave moves over the surface. If the slope is already in the irregular reflection zone, the head wave striking it is already formed. A secondary head wave, much stronger than the first one, is formed close to the slope. It follows from this that on the slopes facing an explosion the effect of the air shockwave is always appreciably increased. Conversely, on the far side, where the wave, having rounded the top of the hill is weakened, the effect of the explosion is accordingly reduced.
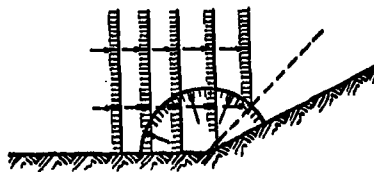
Fig. 33. Variation in shockwave front when it strikes an inclined obstacle (hillside).

If contours are shown on a map, by applying the principles given here we can show how the destruction zone is affected by the topography. Fig. 34 shows contours outlining an elongated hill. Let us assume that an atomic bomb has exploded close to the side of the hill. In Fig. 34 the broken line shows the circular destruction zone which would have been formed during an explosion over flat terrain. The solid line shows the actual size of the destruction zone due to the effect of the hill on the air shockwave.
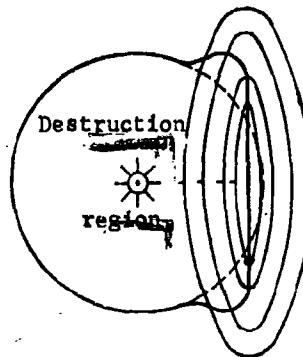
Fig. 34. Variation in destruction region when topography is standard (hill shown by contours).

The principal rule which generally sums up the effect of the topography on an air shockwave is that the wave hitting the near side of, the hill is usually reflected irregularly by it, as shown in Fig. 35. A new head wave stronger than the wave which approached the foot of the hill now moves up the side. The intensification brought about usually ranges between twice the overpressure, for hills with an incline of 35 - 45° or more, and an increase of several percent when the slope angle is 5 - 10°.

It should be pointed out that the greatest intensification of the shockwave is found when the slope increases steadily from the foot to the crest. If the steepness begins to decrease near the top, this means a reduction in pressure at the wavefront. Hence the transition from the near side to the far side, if it is smooth, has comparatively little effect on the variation in the pressure of the shockwave. Naturally, the pressure on the far side is less, but the decrease may begin on the near side if the steepness falls off.

The movement of the wave up A hillside is shown diagramatically in Fig. 35. Here we should note how the wave flows round the crest of the hill, gradually going down the other side. At a certain height above the hill we observe a wedge-shaped area where the effect of the wave is intensified.

If there is a second hill beyond the first one, the wave moves down the first hill and encounters the near side of the second hill, approaching it differently from its approach to the near side of the first hill. This is shown in Fig. 36. In this case the relative increase in pressure when the wave hits the second hill is greater than when hitting the first hill.

In all these cases the topography only has an appreciable effect when the size of the hillside, fold or valley is greater than the depth of the compressed zone behind the air shockwave front.

Thus, an appreciable effect on the air shockwave from an atomic explosion may be exerted by comparatively large regularities of the terrain.
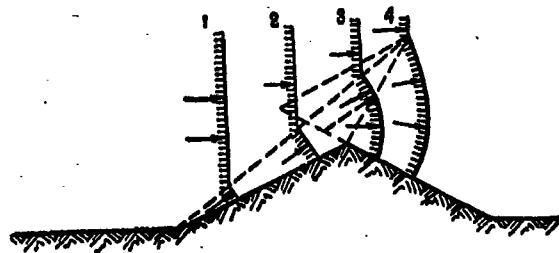
Fig. 35. Successive moments in the flow of a shockwave   a hill.
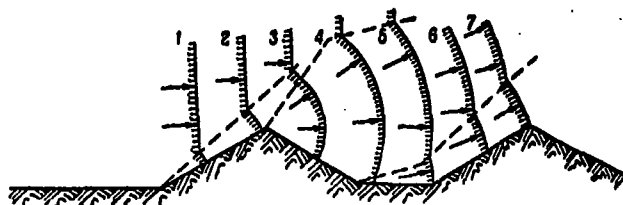
Fig. 36. Successive moments when a shockwave passes over two hills.

Rugged terrain may also have an effect on the air shockwave in that in fairly deep valleys the direction and velocity of the wind, as well as the air temperature, are often very different from when MEASURED ON open country.

Hence, hilly, averagely rugged terrain reduces the destruction zone caused by an atomic explosion, particularly if the hills are higher than 100 m and they slope more than $10°$. Here a higher pressure is created on the slopes facing the explosion, and its destructive effect is greater when it meets an obstacle. On the slopes on the other side there is a peculiar kind of shadow in the area of which the effect of the blast is reduced. It should be kept in mind, however, that in ravines and gulches, the direction of which coincides with the movement of the shockwave, there may be considerable local increase in pressure. In mountainous terrain the destruction zone may be less than on flat country, and the outline of it is distorted by the VARYING topography. In narrow valleys, ravines and gulches, provided the entrance to them faces the explosion, the sharp increase in the pressure of the shockwave may occur to a greater extent than on

-93-

rugged terrain. In the mountains there may also be avalanches of snow or stone some way beyond the destruction zone. An atomic bomb dropped near a gulch or in a narrow river valley with overhanging cliffs may lead to an avalanche accompanied by flooding of the neighboring territory.

6. Effect of weather on propagation and effect of air shockwave

During the explosion of conventional bombs, shells and missiles of different types, when the weight of the explosive is not more than a few tons, the effect of weather on the air shockwave is comparatively slight and not usually taken into account. The greater the charge and the greater its range of destruction, however, the more the weather affects its action. Obviously, in atomic and hydrogen explosions this effect is particularly great. Let us consider it in more detail.

The effect of weather on an explosion depends mainly on two factors: the distribution of the air temperature at different heights above the ground and the distribution of wind velocities at different heights above ground.

Naturally, the effect of these two factors is usually simultaneous and combined. But for greater lucidity we should perhaps consider them separately. Let us first take the effect of temperature.

Effect of temperature on propagation of shockwave. As pointed out above, the velocity of propagation of an air shockwave is

$$D = c \sqrt{1 + 0.86 \frac{\Delta p_\phi}{P_0}}.$$

The quantity $\underline{c}$ in front of the root sign is the speed of sound in air (in meters per sec).

It can be considered that the velocity of propagation of the wave is directly proportional to the speed of sound since within the practical limits of variation of the addend $0.86 \, \Delta p_{\phi} / P_0$, its effect as a first approximation can be disregarded. In turn, the speed of sound depends on temperature. It is directly proportional to the square root of the absolute temperature. As we know, the absolute temperature T is reckoned from absolute zero, which is 270° below zero on the conventional centigrade scale, i.e., $\underline{T} = \underline{t} + 273$, where $\underline{T}$ is the absolute

-94-

temperature, t is the temperature centigrade.

It can be assumed that the speed of sound

$$V_{31} = 332 \sqrt{\frac{273 + t}{273}} \text{ m/sec}$$

Here 332 m/sec is the speed of sound at $0°C$.

Provided t does not vary more than from +60° to -60°, we can base our calculation on the following equation with a fair degree of accuracy

$$V_{31} = 332 + 0.5t.$$

Thus, the speed of sound given above, 340 m, corresponds to a temperature of 15°C.

The temperature of the air usually differs according to the height. For example, on a hot summer day at mid-day the air layer close to the surface of the earth is very hot. This phenomenon is most often observed in summer in bright, sunny weather. The effect stands out most clearly in deserts and arid steppes. The upper layers of air are appreciably colder here and at a height of several kilometers the temperature is considerably below 0°C.

In this case the speed of sound, and therefore the velocity of the shockwave travelling along the ground, are appreciably greater than the speed of sound and the velocity of a shockwave moving vertically upwards, which leads to a change in the shape of the wave front. For example, in a ground-level explosion, as we saw earlier, a shockwave with a surface shaped like a hemisphere is produced in the air which at a constant temperature. But if the temperature of the air decreases with height, the semicircular wave front changes. The wave travels a comparatively long way through the hot air at ground level; conversely, above in the cold air the wave travels a much shorter distance. The change in shape of the wave front resulting from this is shown in Fig. 37. The variation in temperature T with height is shown in the same figure, on the right-hand side.

Shockwaves which are not very strong travel in a direction roughly perpendicular to the wave front. The change in shape therefore leads to a change in the direction of the wave. This is also shown in Fig. 37. It can be seen from the diagram that the wave is curved by the temperature. This means that the bulk of the energy of the shockwave moves away from the ground and the wave is

considerably weakened near it. The further the shockwave is removed from the point of explosion, the more appreciable its weakening becomes. At a distance of 10 or 20 km there can be a reduction in the overpressure under favorable conditions, and this may lead to a reduction in the radius on the corresponding destruction, for example, shattering of window panes. But broken windows can also be a source of injury if there are people nearby in the buildings.
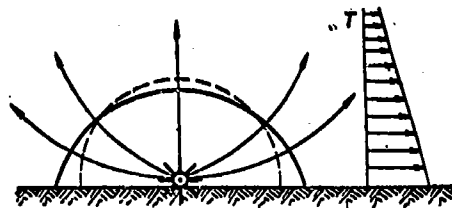
Fig. 37. Deviation of direction of propagation of shockwave when the air near the ground is warmer.

Thus, it can be assumed that on a hot summer day, when the air near the ground is very hot, the effect of the air shockwave is greatly reduced over distances of the order of 10 km or more, and that this appreciably reduces the effectiveness of an atomic explosion.

The exact opposite occurs when the temperature distribution of the air is the reverse, as shown in Fig. 38. The air close to the ground is very cool, while up above there are warmer masses of air. HIGH/the wave RISES very rapidly, WHEREAS THE MOVE NENT NEAR the ground/ ISSLOWER. This means that the shockwave front in the air changes shape, as shown in Fig. 38. The diagram shows how the paths of the wave curve down towards the ground. This is exactly the opposite pattern to what can be seen in Fig. 37. When the paths of the shockwave curve downwards, the effect of the explosion in the layer of air close to the ground is intensified, and the destructive range may be considerably increased, provided its original size was approximately 10 km or more.

An air temperature distribution in which the coldest layers are below,
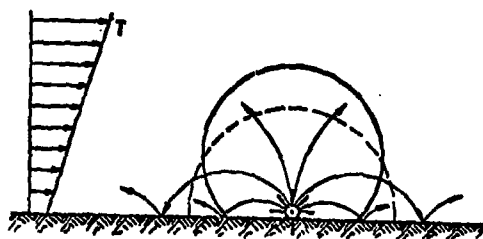
Fig. 38. Deviation of direction of propagation
of shockwave when the air near the ground
is colder

near the ground, usually occurs on xxclear, cold nights, particularly at dawn when there are light frosts spring or/the fall) or else during heavy winter frosts. Under these conditions the effectiveness of atomic and hydrogen bombs is accordingly increased.

Effect of wind on propagation of shockwave. Let us look at the effect produced by wind on a shockwave. It is sometimes conjectured that wind may intensify the effect of the shockwave since the pressure of the wind is added to the pressure of the shockwave if it is moving in the same direction. But if the wave is moving against the wind, the former may be weakened. This view is correct, but it does not take into account another, much stronger effect/by the wind.

The velocity of the wind usually varies with its height above the earth's surface, and in most cases is lower near the earth and higher up above (Fig. 39). Under these conditions the wind changes the shape of the wave front to some extent or other. WHEREAS the wave front is shaped like a regular hemis- here during a ground-type level explosion in homogeneous and stationary air, if here is a wind increasing with height the wave front will be, as it were, squashed in the direction of the wind. This is shown in Fig. 39.

The curvature of the wave front, just as in the influence of temperature on the wave, leads to curvature of the paths of the wave. A characteristic effect of the wave in this case is the sharp difference between the paths of the wave on the windward side and the leeward side (Fig. 39). On the windward side, the shockwave is deflected upwards and is detached from the ground. Conversely, on the other side the curvature of the wave results in intensification of its action. The result may be that in the direction of the wind the effect of the explosion is transferred several times further than if there were no wind. Conversely, the distance is reduced several times when the wave moves into the wind. The all-round effect is that the destructive range is increased and shifted when there is wind.

If there is wind and variable temperature at the same time, the effect

shockwave may be still greater. For example, if a light frost is followed by a strong wind increasing with height and blowing over cold ground, the increase in the effect of the explosion in the same direction as the wind is particularly great. Conversely, on a hot summers day the effect of the wind should be far weaker. The greater the caliber of the charge, the more these effects are manifested.
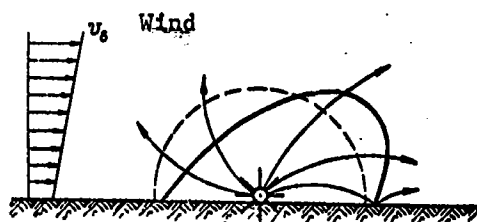
Fig. 39. Propagation of shockwave when the wind increases with height.

7. Shockwaves in dense media.

Shockwaves in water during underwater nuclear explosions. When nuclear weapons are used against ships, docks and hydrotechnical constructions, AN underwater explosion may prove extremely effective. An underwater explosion is quite different from one in the air. Provided the charge is immersed deeper than 15 - 25 m (depending on the caliber), the light and penetrating radiation do not escape from the water, but are absorbed by it. The absorbed energy causes the formation of large masses of water vapor which quickly expands, throwing up an enormous column of water more than a kilometer high, and partially using the energy to form a powerful shockwave in the water. The shockwave in water is in principle of formation more or less the same as in the air, and is qualitatively similar to the latter. On the outside the wave is bounded by a sharp jump in densification (wave front). The pressure of the water is greatest at the front. Behind the front it gradually decreases, approaches normal and then falls slightly below normal.

The velocity of propagation of a water shockwave is more constant than

the one in air, and fairly high. It virtually coincides with the speed of sound in water (about 1500 m/sec).

Over the same distance, the pressure at the shockwave front in water is much greater than in air. This is due first and foremost to the considerable density of the water and its low compressibility.

A characteristic feature of the shockwave in water is that when it encounters a stationary obstacle, its pressure is only slightly increased. This is because the velocity of motion of water behind the wave front is very low, since water is only slightly compressible and there is no where to shift it when the wave moves forward.

The time over which the overpressure acts in the water is smaller than in air by a factor of 130. The depth of the wave is comparatively slight. It depends on the depth at which the charge exploded. Indeed, if the explosion of a nuclear charge takes place at a comparatively slight depth, the water shockwave quickly reaches the surface. Here the pressure at its front leads to extremely rapid detachment of the surface layer of water from the remainder. The layer is atomized into fine spray which is hurled into the air with great force. The layers of water beneath seem to seethe and turn into foam. All this leads to the almost instantaneous disappearance of the overpressure. A rarefaction wave is formed at the surface and begins to move downwards into the depths at a velocity equal to the speed of sound in water. Since the rarefaction wave . spreads through water further densified by the compression wave, it catches up the compression wave and partially enters the compressed water zone, where it *releases* the overpressure. The mutual effect of the compression and rarefaction waves is shown in Fig. 40.

When looking at this diagram, it must be taken into account that the rarefaction wave has the same spherical front as the compression wave. But the center *around* which the circumference *of* the rarefaction wave front should be drawn is shifted upwards with respect to the center of the explosion. The center

of the rarefaction wave is the same height above the water surface as the depth of the charge in the water. Right on the surface the width of the compressed zone is zero, while beneath it the width increases and eventually attains its original size at a certain depth.

The rarefaction wave . reduces THE destruction CAUSED BY AN UNDER-WATER explosion, and/to a considerable extent. The less the depth to which the charge descends, the more marked this effect is. Hence in shallow reservoirs with a FIRM bottom, where the nuclear charge cannot in most cases penetrate the solid rock forming the bottom, there is less destruction during an atomic explosion than when the water is much deeper. Thus, even considering the reflection of the shockwave from the bottom (within certain limits), shallow water is a means of protection for ships, port installations and other objectives by the side of stretches of water or actually in them. It is pointed out in the foreign press that still better protection for particularly important objectives (for example, powerful dams, large power stations) CAN BE obtained by covering the water surface with rafts or pontoons with a solid layer of stones, that is to say by "armor plating" the surface of the water so that the nuclear rocket or bomb explodes on the surface or at a minimum depth.

Shockwaves in the ground. Ground shockwaves are produced whenever there is an explosion on the ground or A LITTLE WAY beneath it. In these cases the explosion has a direct effect on the ground, causing the movement of particles and an increase in pressure in more or less the same way as during a water explosion.

There is another way of producing shockwaves in the ground. An air shockwave or a water shockwave may affect the surface. This causes a shockwave in the ground, and above ground the pressure of the shockwave is equal to the pressure of shockwaves in water or air. As the wave moves through the ground, it is greatly changed, the pressure in it is appreciably reduced while the time is greatly increased.

This is due to the following facts. Soils such as sand, clay, loam, etc., usually have a definite structure. The particles in the soils are arranged in a definite position and when a force is applied to the soil, there is first compression and a slight movement of the particles with respect to each other. But the structure of the soil is unchanged. If the force applied to the soil increases, there is displacement of the particles and they lose their original order. The structure of the soil is destroyed, there is considerable densification and a new, denser structure is created, which can usually withstand greater loads without further destruction.

These changes in the soil when loads are applied to it also occur when a shockwave passes through the ground. Here small overpressures are transmitted most rapidly of all. This is due to the fact that at small overpressures the structure of the soil is not destroyed and is able to transmit the shifts and the loads at great velocity. Heavier loads destroying the structure of the soil and compressing it extensively are transmitted slowly.
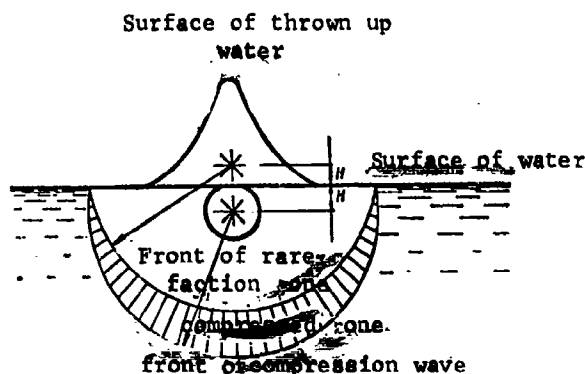
Fig. 40. Compression and rarefaction waves in underwater explosion

Hence large overpressures usually spread more slowly through the ground than small overpressures. In this respect soft soils are markedly different from air or water, in which we see the opposite: the greater the overpressure, the more quickly it is transmitted.

The distribution of overpressure through the shockwave in the ground is thereby considerably different from that in air or water. This is shown diagramatically in Fig. 41 which contains graphs for the variation in overpressure with time in an air shockwave impress*ed* upon the ground, and in the wave at different depths below ground. Since the small initial compressions are transmitted more rapidly than the stronger ones, the maximum pressure moves further and further back and keeps decreasing, while the wave is stretched out more and more. These features of shockwaves in the ground prevent us calling them shockwaves since a shockwave is usually one in which the overpressure jumps to the maximum value in the beginning of its effect, and the pressure peak is shifted forward to the wave front.
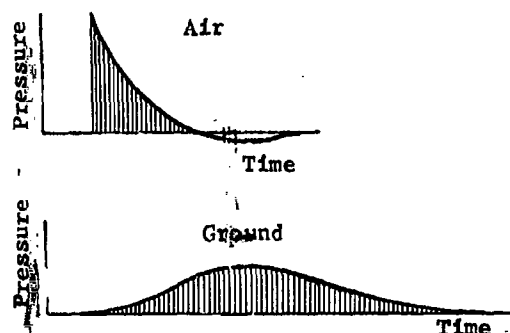
Fig. 41. Variation in pressure in air and in ground during explosion.

An increase in the time over which the wave acts, deceleration of the increase in overpressure and reduction in maximum pressure of the wave lead to

of a

Less / destructive effect.

On account of this, underground constructions, even those a few meters below ground, are usually well protected from explosions occurring in the air.

-102-

If the charge explodes below ground, however, and fairly deep down as well, the effect is rather different.

Under these conditions the bulk of the explosion energy is transmitted to the surrounding ground and causes a powerful shaking similar in action to an earthquake.

Hence shockwaves and their destructive effect are termed seismic and the corresponding quantity R is termed the seismic range.

The seismic effect of a nuclear explosion in soft soil is very powerful indeed, particularly if the soil is moist, for example, when the groundwater level is high, and when the soil stretches further than the destructive range of the corresponding airwave.

The seismic range is several times smaller in rock. But this applies to the area where the effect is comparatively strong. At greater distances, conversely, the seismic effect dies away more rapidly in soft ground and is transmitted through rock in a less weakened state.

At comparatively large distances from the center of an underground explosion, such a high velocity is imparted to the soil that it is thrown a considerable distance and a crater is formed.

The soil thrown up from the crater may travel a long way and injure people, damage buildings and equipment or simply bury them. Under these circumstances the air shockwave is basically vertical and the damage caused by it close to the ground should be comparatively small.

8. Destructive effect of shockwave

Effect of shockwave on humans. The nature and degree of harm suffered by humans during a nuclear explosion depend on the FOLLOWING conditions at the moment of the explosion: distance from the center of the explosion, position at the moment of explosion, degree of protection, and so on. If a shockwave acts on an unprotected person, it may cause various injuries, basically the same kind as those caused by conventional shells and bombs. But the area of destruction during a nuclear

explosion is far greater than when using conventional weapons.

Shockwaves from a nuclear blast have a direct effect on humans and animals, and also an indirect effect if the people and animals are hit by flying or falling masonry. In the case of direct effect, the shockwave may cause *FATAL* injury to the human organism only when the overpressure at the wave front reaches a certain point.

In this case the shockwave ca~uses injury to the lungs, *AND* tympanum and causes hemorrhage. During the atomic bombing of Hiroshima and Nagasaki by the Americans, there were cases of *FATAL* injury through the direct effect of the shockwave at 800 m from the eipcenter of the explosion. At this distance the pressure at the wave front was $1.2 - 1.3$ kg/cm^2.

But *WHEN* the nuclear bombs *WERE DROPPED* (on the Japanese cities, the direct effect of the shockwave was not the main reason for the killing and wounding of people. The main part was played by the indirect effect, that is to say destruction caused by secondary factors: falling masonry and fragments carried by the shockwave. The indirect effect was the cause of injuries and damage of a very varied nature, ranging from minor scratches and bruises to *LOSS OF LIFE*. The indirect effect of the shockwave led to injury at considerable distances. Cases were recorded in Hiroshima and Nagasaki of people being struck by bits of masonry at distances of up to 3200 and 3700 m from the epicenter of the explosion, and people being seriously *INJURED* at distances up to 2000 m. In Hiroshima and Nagasaki the shockwave indirectly claimed most of its victims among people hiding in buildings in which the probability of being struck by masonry was greatest.

The injuries caused by the shockwave are usually subdivided into minor, medium, serious and extremely serious injuries.

Minor injuries occur when the overpressure in the shockwave ranges between 0.2 and 0.4 kg/cm^2 and are known to be caused by an intermediate atomic bomb exploding in the air at distances up to 2.5 km. They are characterized by temporary loss of hearing, slight concussion, bruises and *THE DISLOCATION OF LIMBS*

-104-

Medium injuries occur when the shockwave pressure is approximately 0.5 kg/cm^v and are observed at distances up to 2 km from the point of the explosion of an intermediate bomb. Here there may be serious concussion of the entire organism, damage to the hearing, bleeding from the nose and ears, fractures and serious dislocations of the appendages.

Serious injuries occur when the shockwave pressure is greater than 0.5 kg/cm^v and have been known at a distance up to 1.5 km from the point of explosion of an intermediate bomb. Heavy concussion of the entire organism, excessive bleeding from the nose and ears and serious fractures OF the appendages are characteristic. [1]

Pressures greater than 1 kg/cm^v cause extremely serious injuries.

Among the victims in Hiroshima and Nagasaki about 70% had open wounds (cuts and jagged wounds); and 10 - 20% suffered contusions and fractures. The cause of more than 60% of the open wounds was flying glass, bits of buildings, and more than 50% of the contusions were due to falling masonry. The injuries caused by flying objects and falling masonry comprise 70 - 80% of all cases. [2]

According to foreign press reports, as many as 50% of the fatalities in Hiroshima were due to the effect of the shockwave. It should be pointed out that in certain cases the shockwave had a different effect on humans, even at the same distance from the epicenter. The reasons for this are that a mode of propagation of the shockwave is not always the same. Different local objects, for example, buildings and the topography, for example, hills, elevations, and so on, have a screening effect on its propagation. Let us quote some characteristic cases of the direct action of the shockwave during the atomic explosions over Hiroshima and Nagasaki. People who were standing on the dam 800 m from the epicenter at the moment of the explosion were thrown in the river. One man 1200 m from the epicenter was hurled 10 m, while another standing 200 m from the epicenter was knocked over. People located in a mountain 900 m from the epicenter lost their headwear. That was the direct effect of the shockwave produced by the

1/ see page 108.
2/   "

explosion of a nuclear bomb with a TNT equivalent of 20,000 tons.

We should also point out that in populated points the shockwave may cause conflagrations by destroying stoves and damaging gas pipes and electric cables. The fires themselves may cause injury.

Effect of shockwave on different installations and objectives. The destructive effect of an air shockwave is due to the fact that when it encounters an obstacle in its way, it exerts a tremendous pressure on it. For example, if the air shockwave encounters a house, it first hits the wall facing it. The moving mass of air impresses upon the wall, first because the air is greatly compressed, and second, because its movement is restrained by the wall and the energy of motion becomes energy of pressure, the latter being increased accordingly. The densified mass of air slowly begins to flow round the edges of the wall after it has formed. The area within which the air begins to move round the edges is rapidly increased, and in a short space of time practically the entire mass of air densified during the impact is set in motion around the obstacle.

In view of this, the initial force acting on the house is reduced. The reduction is due first and foremost to the fact that there is a decrease in the pressure in the mass of air densified by the wave at the front wall. Furthermore, as shown in Fig. 42, the wave traveling round the building exerts pressure on it from behind and at the side, and also increases the pressure of the air inside the building when it enters through the windows and doors.

Characteristic destruction due to the air shockwave is the breaking of window panes, which occurs at overpressures of several hundreds of a kilogram per square meter. In this case a window plane, let us say 0.5 x 0.5 m in size, that is to say with an area of 0.25 m^2, experiences a load of at least 25 kg. This is obviously quite enough to break the glass. It should be pointed out that an over-pressure acting for some time can hurl bits of broken glass inside the building with such force that they may cause serious injury to the people inside.

Underground shelters with coverings which do not protrude above the surface
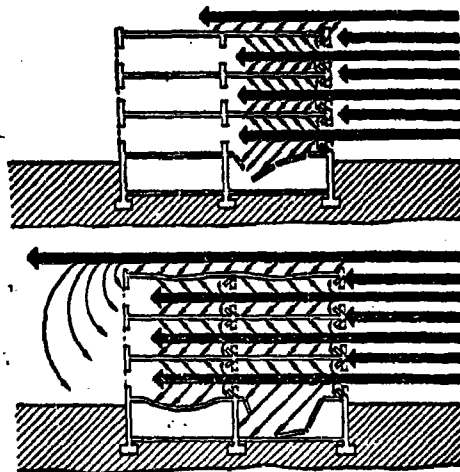
Fig. 42. Flow round and entry into building by shockwave.

of the ground experience more or less the same specific pressure as the surface itself. If the wave travels along the ground, that is to say, if we are dealing with a ground-level shockwave or head wave caused by irregular reflection during an aerial explosion, the pressure on   top of the shelter is equal to the over- pressure of the air at the wavefront.

Overpressures of several kilograms per square centimeter or several dozen tons per square meter can be withstood by ordinary wood and earth field shelters and airraid shelters.

Shelters made of solid ferroconcrete or ferroconcrete parts can withstand the effects of an intermediate atomic bomb shockwave at any point, including even the epicenter, that is to say directly below the point of explosion. This is so provided the height of the point of the explosion above the ground is not less than 300 m.

Let us consider the effect of a shockwave produced by the explosion of a charge with a TNT equivalent of 20,000. The considerable damage at Hiroshima and Nagasaki was mainly due to the effect of the powerful shockwaves. The degree of damage caused to buildings and their stability in an atomic explosion depend first and foremost on the power of the explosion and also on the type, strength, and size

-107-

of the building, the materials with which it is built, its position amid local objects and on the terrain, and finally, its distance from the point of explosion.

Single-story concrete buildings (factories) at Hiroshima were severly damaged at distances up to 1600 m from the epicenter of the explosion. Multi-story buildings with ferroconcrete framework as well as industrial premises with steel frameworks were totally demolished at distances up to 700 m, and suffered serious damage at distances up to 1500 m from the epicenter.

Brick buildings without any framework were destroyed at greater distances than those with frameworks or ferroconcrete buildings. Buildings made of brick without framework were totally destroyed at distances up to 1600 m from the epicenter. Light, wooden residential houses, with framework, were destroyed at distances up to 4,000 m from the epicenter.

The destruction ranges for buildings and military equipment are given in Fig. 43.

During the aerial explosion of a nuclear charge with a TNT equivalent of 20,000 tons (height of explosion $H = 600$ m) serious damage may be caused to tanks 200 m from the epicenter, radar equipment up to 1200 m from the epicenter, AND aircraft on the ground at distances up to 1600 m. Glass may be broken at distances up to 8 - 12 km from the point of explosion.

The following approximate data are for damage caused to warships of different classes. A warship may be put out of action entirely or severly damaged at distances up to 800 - 1000 m from the center of explosion of an intermediate charge; serious damage may be done to superstructures, boilers and equipment at 1000 - 1200 m; intermediate damage can be caused up to 1350 m and slight damage

1) "The effects of Atomic Weapons", New York, 1950.

2) Kh. Matsuva, K. Khalsi. Nuclear Weapons and Human Beings. Translations from the Japanese. Foreign Literature Press, 1959.

-108-
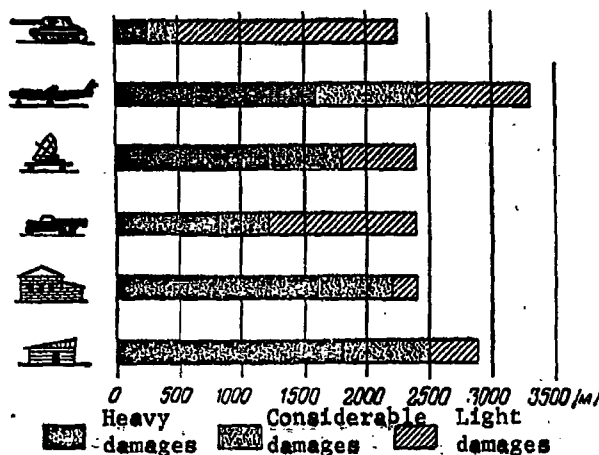
Fig. 43. Range over which buildings are destroyed and military equipment

damaged during atomic bomb explosion ($\underline{q}$ = 20,000 tons).

up to 1650 m. Obviously, the amount of damage depends on the class of the ship.
The explosion conditions (depth of the water, depth of the explosion, and so on)
also have an effect on the range.

As the caliber of the nuclear charge is increased, the destructive range
of the shockwave increases in proportion to the square root of the explosion energy,
and not to the caliber of the bomb. For example, if the power of one bomb is 1.000
times greater than another, the destructive range of the shockwave of the first
bomb is $\sqrt[3]{1000}$ times greater than that of the second, i.e., a factor of 10.

It is interesting to note that as the caliber of the nuclear charge is
increased, its effectiveness, generally speaking, decreases (if we take the area
of destruction per unit of TNT equivalent as the index of effectiveness). Indeed,
the total area of destruction $\underline{S}$ caused by an atomic shockwave is proportional to
the TNT equivalent $\underline{q}$ raised to the power 2/3, which can be written down as follows

$$S = aq^{2/3},$$

where $\underline{a}$ is the proportionality factor.

But the specific area of destruction $\underline{S}_1$ per unit of TNT equivalent $\underline{q}$ may
be written as $\qquad S_1 = \dfrac{S}{q} = \dfrac{aq^{2/3}}{q} = \dfrac{a}{q^{1/3}}.$

-109-

Hence, as the caliber is increased, the specific area of destruction is reduced in proportion to the square root of the TNT equivalent.

Let us look at another example. Let us assume the total area of destruction of a charge with a TNT equivalent q_T = 20,000 tons is 3 km^2. The specific area then will be

$$S_1 = \frac{3\,000\,000}{20\,000\,000} = 0.15 \ \text{m}^2/\text{kg}$$

For a charge with q = 100,000 tons, the destructive range of the shockwave is increased $\sqrt[3]{\frac{100\,000}{20\,000}} = \sqrt[3]{5}$ while the total area of destruction is increased $\left(\sqrt[3]{5}\right)^2$ and in the given case is $3 \cdot \left(\sqrt[3]{5}\right)^2 = 8.79$ km^2. But the specific area of destruction is

$$\frac{8\,790\,000}{100\,000\,000} = 0.0879 \ \text{m}^2/\text{kg}$$

that is to say an increase in caliber of five reduces the specific area of destruction by $\sqrt[3]{5}$.

The shockwave from a nuclear explosion may cause fires, apart from mechanical damage. It may destroy $\overset{COAL}{STOVE\ BURNING}$/or wood, it may cause short-circuits or destroy gas pipes, and so on. At industrial plants there may be destruction of furnaces, boilers, $\overset{or}{|}$ the collapse of buildings. These factors may produce fires as a consequence of the shockwave.

The shockwave also helps to spread fires. It breaks window panes, demolishes fire-prevention partitions, demolishes walls and roofs, tears the plaster off wooden walls and ceilings, breaks down doors, landings, floors and so on. Burning debris from neighboring buildings may come flying in through the windows or holes, helping to spread the fire, even in fire-resistant buildings. Inflammable material may be hurled across courtyards and streets by the shockwave.

It should be pointed out, however, that the destruction of buildings by the shockwave may also prevent the spreading of fires. Buildings with inflammable framework may collapse and as a result not burn so rapidly.

Other factors promoting fires are the possible damage to water supply systems and the partial or total disorganization of the fire service. For example, in Hiroshima and Nagasaki damage was caused to the water supply system and main pipelines, which resulted in leakage and a drop in pressure. A large number of pipes laid on the surfac e of the ground were destroyed by falling masonry. The main pipeline in Nagasaki which was about a meter on the ground was destroyed by uneven shifting of the soil due to the shockwave. In Hiroshima this pipeline was destroyed through the destruction of the bridge across which it ran. In Hiroshima about 70% of the firefighting equipment was buried under falling masonry, not to mention the fact that about 80% of the firemen themselves were unable to carry out their duties. Even if the people and equipment had not suffered, however, in many cases they could not reach the center of the fire through the RUBBLE blocked streets.

CHAPTER III

LUMINOUS RADIATION FROM A NUCLEAR EXPLOSION

1. Source of luminous radiation in a nuclear explosion

As has already been pointed out, during a nuclear explosion in the air, approximately one third of the energy released is radiated in the form of light (or more exactly, radiant energy) while the remainder is emitted in the form of a shockwave, radioactive radiation and thermal energy carried along in a hot cloud.

For example,   a nuclear charge with a TNT equivalent of 20,000 tons releases approximately seven billion kilocalories in the form of light. This amount of heat could heat up 70,000 tons of water from 0° to boiling point.

The source of the light during a nuclear explosion is the luminous area shaped like a ball (in an aerial explosion) or hemisphere (in a ground-level explosion).

The fireball formed is in many respects like the sun. In both cases the radiation consists of ultra-violet light with a comparatively short wavelength, visible light with a longer wavelength and infra-red radiation, the wavelength of which is still greater. The luminous radiation from a nuclear explosion is the totality of the visible light and ultra-violet and infra-red areas of the spectrum close to it.

Just as the sun, the luminous region   constitutes   incandescent gas heated to a very high temperature by the energy released. It consists of evaporated material from the nuclear charge itself, fission products from the atomic charge and air adjoining the point of the nuclear explosion. The luminous region differs from the sun in that the nuclear reaction on the latter is continuous, so that the sun has now been radiating light for more than 4 billion years. Furthermore, since the nuclear reaction inside the sun is continuous, the temperature of its surface remains constant and equal to about 6000°.

During any nuclear explosion the luminous area, which is also the result of the nuclear reaction, that is in size and surface temperature; its dimensions increase with time to a certain point after the explosion, while the surface

temperature falls. This will be discussed in greater detail later on.

As it / Spreads at A. velocity of 300,000 km/sec

over great distances from the point of the explosion, the luminous radiation is absorbed by various bodies and turns almost completely into heat. As a result the illuminated bodies become hot. The heating of the surfaces of different bodies To high temperatures is what causes the damaging effect of luminous radiation from an atomic explosion. It may cause burns, it may ignite different materials and may even melt metals.

It is known that the explosion of conventional bombs, mines and shells is also accompanied by luminous radiation, although it is very different from that of an atomic explosion. The difference is that in a conventional explosion the luminous area occupies a small space while the flash lasts a very short time (thousandths of a second), hence it does not cause any damage.

In an atomic explosion the situation is quite different.

Here the cause of destruction to buildings and injury to people is mainly THE shockwave. But luminous radiation may strengthen the effect of the explosion by causing burns on humans and animals, by causing conflagrations, damaging military equipment and setting fire to buildings. That is why luminous radiation from an atomic explosion is one of the damaging factors.

As is known, light comprises electromagnetic waves of a certain wavelength. It is emitted by certain atoms and molecules when they are excited.

The excitation of atoms in matter can be brought about by heating it. It is known that heated bodies glow; this is due to the fact that atoms in the molecules and molecules in the bodies are in a state of constant motion. The motion is a universal property of all particles of matter, of which the universe consists. The temperature of the body is determined by the velocity of motion of the molecules. When we heat or cool a body, we accelerate or decelerate the motion of the particle. This idea was first expressed by the great Russian scientist Lomonosov. While in motion, the particles keep colliding. If the temperature of the body is low, these collisions do not disturb the order in the arrangement of

-113-

electrons throughout the atom, but what happens if we heat the filament of a bulb to a temperature close to 1000°? At this point the tungsten atoms move far more rapidly and experience sharp jolts when they collide. These jolts leave their marks on the atom; the outer electrons acquire *SURPLUS* energy and move from the closer orbit to one further away, and the atom is "excited". Changing from the excited to the normal state, the atoms give off light of a certain wavelength (frequency).

Experience shows that the energy of an atom cannot change continuously, cannot have just any value. It varies in jumps by certain finite amounts, differing in different atoms.

This means that the energy of an atom can only have certain selected values characteristic of each atom. And this means that each atom emits light of a certain frequency (wavelength).

But why is the spectrum of incandescent solids and liquids (and also gases) under high pressure *AND* continuous, that is to say, why is the energy emitted on different wavelengths including infra-red and ultra-violet bands? This is due to the fact that any body consists of an enormous number of atoms present in different energy states and *THAT* the conditions under which they interact are different. Hence, different atoms emit light of different wavelengths. On account of this the bodies emit electromagnetic vibrations over a wide *WAVE BAND*

The distribution of radiant energy according to wavelength, that is the spectral composition of the radiation, as well as the total amount of radiant energy, are determined basically by the temperature of the body. The higher the temperature, the more energy in the ultra-violet region of the spectrum, and the greater the total amount of energy radiated.

Incandescent bodies emit light with wavelengths ranging from thousandths of a micron (ultra-violet light) to thousands of microns (infra-red light). Of this large range of luminous wavelengths, only a small part can be perceived by the human eye. Shorter wavelengths (ultra-violet) and longer wavelengths (infra-red) can only be detected by means of special devices. The electromagnetic

radiation known at the present time can be broken down according to wavelength or frequency into an electromagnetic wave scale (Fig. 44). As can be seen from this figure, the scale is divided into several regions. It should be kept in mind that this division is arbitrary (relative) and not strict. It is mainly based on the methods of deflecting (manifesting) the · ¨radiation.

Ways of producing electromagnetic waves are greatly varied. Waves ranging from radiowaves to infra-red light can be obtained by purely electrical methods (using oscillating circuits).

But over most of the infra-red region the wavelengths are too small to be generated by electric oscillating circuits, and the principal infra-red spectrum is obtained by radiation from heated bodies. Hence infra-red radiation is termed heat. It occupies the region of the spectrum starting roughly at 0.76 microns and ending at several hundred microns, between the red section of the visible spectrum and the ultra-short radiowaves. When the temperature of a heated body is raised, the radiation becomes visible. Fig. 44 shows that out of the whole of the electromagnetic spectrum the area occupied by visible light is very small. It is the electromagnetic waveband lying between 0.4 and 0.76 microns.
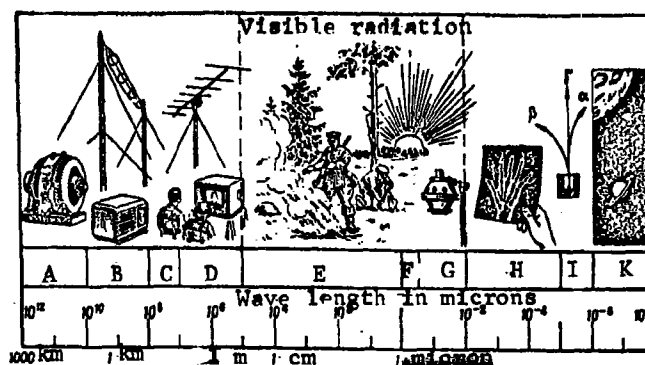
Fig. 44. Overall electromagnetic spectrum: A) AC generator radiation; B) radio broadcasting; C) short radio waves; D) ultra-short radiowaves; E) infra-red light; F) visible light; G) ultra-violet light; H) x-ray; I) gamma ray; K) cosmic rays.

The light produced by an electric arc or by quartz or mercury lamps contains both visible and ultra-violet rays. The latter overlap with x-rays.

X-rays are obtained by x-ray tubes when targets made of heavy elements (tungsten, molybdenum) are bombarded by electrons moving at high velocities.

Gamma rays are emitted by atomic nuclei during nuclear reactions. Cosmic rays are also engendered by processes occurring in atomic nuclei. Waves of the same length can be produced by a large number of different methods. For example, gamma rays, as is well known, are emitted by atomic nuclei, but electromagnetic radiation of the same wavelength may be obtained in x-ray tubes.

An increase in the velocity of the bombarding electrons leads to a higher frequency (lower wavelength), and the x-rays change to gamma rays. Here is another example: ultra-violet radiation with a wavelength 10^{-6} cm occurs during a gas discharge. The same radiation may be obtained in an x-ray tube.

It should be pointed out that the radiation of the same wavelength, but derived by different methods exhibits the same properties, since they are all the same in nature - electromagnetic waves. The properties of radiation are determined not by the method used to produce it, but by the wavelengths along (frequency).

Laws governing radiation of luminous region of nuclear explosion. The light sources emitting luminous energy due to an extensive rise in temperature are termed temperature sources.

The concept of an absolutely black body has been introduced to establish the laws governing temperature sources. An absolutely black body is one which entirely absorbs all incident luminous radiation, no matter what the wavelength. There are no bodies in nature possessing this absorptive capacity. A model of an absolutely black body has nevertheless been constructed for study of properties of temperature sources. The model is a hollow sphere or hollow cylinder with a small opening and the inside surface is coated with black. Any ray entering this body through the small hole will not emerge before it has undergone numerous reflections. Let us assume that the absorptivity of the inside surface is 90%. During the very

-116-

first reflection the reflected flux is 10% of the incident flux, during the second reflection it will be 1% of the incident flux, and during the next reflection 0.1%.

If the ray of light emerges after the third reflection, the total absorptivity (ratio of absorbed luminous flux to incident flux) is 0.99, that is to say, close to unity. The nearest approach to an absolutely black body is a platinum soot or bismuth black, the absorption power of which is about 98%.

Thus, when the beam o f light enters the hole, virtually all the luminous energy stays inside the cylinder (does not come outside) on account of multiple reflection from the inside walls. From the practical point of view, this model may be termed ans absolutely black body which entirely absorbs all incident rays.

A body of this kind does not only possess the maximum absorptive capacity, compared with other bodies, but also the maximum emissivity.

If the inside walls of this model are made white hot by an electric current or some other method, the hole will shine with the greatest brightness possible at this temperature on account of multiple reflection inside the hollow body.

Theoretical and experimental investigation have shown that at any set temperature an absolutely black body emits the greatest quantity of luminous energy compared with any other temperature radiators. The radiation of an absolutely black body, is, therefore, the limit which is approached to some degree by other, less perfect temperature sources.

Many incandescent bodies, including gases, also possess considerable absorption capacity. It has been established by numerous experiments that the *IN THE MAIN* same laws hold for sunlight as for radiation of black bodies

The luminous region of the atomic explosion is also a temperature source.

As has been pointed out, in an atomic explosion, the sources of luminous radiation are (as in the case of the sun) incandescent vapors and gases. Hence, we can assume with *REASONABLE* accuracy for practical purposes that the luminous region of the atomic explosion emits light like an absolutely black body. Let us not

-117-

consider the laws consider the laws governing radiation from these bodies. The laws include the following:

1) the intensity of the luminous radiation $I_0^\wedge$ is the amount of luminous energy emitted from one square centimeter of surface of an absolutely black body per second and is proportional to the fourth power of its absolute temperature $T^\circ K'$. This law which is known as the Stefan-Boltzmann law is expressed mathematically in the following way

$$I_0 = \sigma T^4 \ cal/cm^2 \cdot sec$$

where σ is the constant equal to $1.37 \cdot 10^{-12} \ cal/cm^2 \cdot sec \cdot deg^4$;

T is the absolute temperature of the radiating surface in $^\circ K$.

This law shows the exceptionally strong effect of the temperature of the body surface on its power to radiate luminous energy. When the temperature of the surface is raised by a factor of 2, the intensity is increased 16 times, when the temperature is trebled, the intensity is increased by a factor of 81, and so on.

The total amount of luminous energy radiated by a body from its entire surface during the time it is luminous t_0 is determined by the following equation (provided the size of the body and the temperature of its surface do not vary with the time it is luminous)

$$E_{rad} = \sigma T^4 t_0 .$$

E_{rad} is usually measured in calories.

2) The spectral intensity of radiation I_λ is the amount of luminous energy in calories radiated from $1 \ cm^2$ of body surface per sec over the range of wavelengths from λ to $(\lambda + 1)$ micron and is determined by Plank's equation

$$I_\lambda = \frac{C_1}{\lambda^5 \left(e^{\frac{C_2}{\lambda T}} - 1 \right)} \ cal/cm^2 \cdot sec \cdot micron$$

where λ is the wavelength in microns;

T is the temperature of the body surface in $^\circ K$;
C_1 and C_2 are constants equal to

$C_1 = 8.85 \cdot 10^3 \ cal \cdot micron^4 /cm^2 \cdot sec$

$$C_2 = 1.44 \cdot 10^4 \text{ micron} \cdot \text{deg.}$$

It follows from Planck's formula that for an absolutely black body the spectral composition of the radiation is only a function of the body temperature. Fig. 45 shows curves for the spectral intensity of radiation I_λ calculated from Planck's formula for different surface temperatures of an absolutely black body.
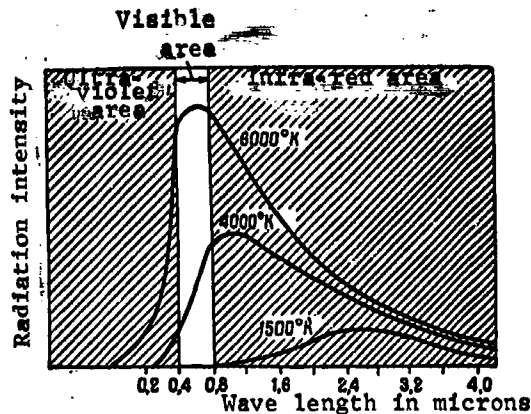
Fig. 45. Graphs showing variation in spectral intensity of radiation for different temperatures of surface of an absolutely black body.

It can be seen from these graphs that the higher the temperature of the body, the greater the intensity of radiation in each sector of the spectrum and therefore, the greater the total radiation energy. Furthermore, it follows from the graphs that when the temperature is raised, the greatest spectral intensity (the maximum on each curve) shifts towards the shorter wavelength. This effect has been termed Wien's displacement law.

3) In accordance with the displacement law, the wavelength λ_m at which the intensity of radiation is greatest is a function of the absolute temperature in the following way

---
1)

The absolute temperature T is reckoned on the so-called Kelvin scale and starting at absolute zero at $t = -273\,°C$ and is designated $T\,°K$. The conversion of centigrade (C) to absolute temperature (K) is made by the equation $T\,°K = (t + 273\,°C)$.

For example: $6000\,°K = 5727 + 273\,°C$.

$$\lambda_m = \frac{2886}{T} \text{ micron}$$

We get the following values of λ_m (in microns) for different temperatures

2000°	6000°	8000°	10 000°	20 000°	50 000°
1.44	0.48	0.36	0.29	0.14	0.058

The color of the radiation also varies with the shift of the maximum on the radiation curve - from red at low temperatures to white at higher temperatures.

The following pattern can be established for the radiation of luminous energy by hot bodies on the basis of study of energy distribution in the spectrum at different temperatures.

Bodies radiate energy at any temperature. At lower temperatures they mainly radiate infra-red light, which corresponds to very long wavelengths; and the total amount of energy is small. When the temperature is raised, rays corresponding to shorter wavelengths are added, the total amount of energy is increased and the energy maximum shifts towards the shorter waves. It is only at temperatures slightly above 500°, with an overall increase in the amount of radiated energy, that the first visible rays (red) become so intensive that they begin to stimulate the eye. Finally, at temperatures above 1000° we find violet rays, the whole of the visible spectrum now appears, there is then white heat and we then detect ultra-violet light.

As can be seen from the curves in Fig. 45, emission in the visible region only constitutes a small part of the total energy radiated by the luminous body.

Generally speaking, the relatively greatest visible radiation (approximately 45%) occurs at a temperature of 6700°K. When the temperature is raised above this point, there is a considerable increase in the intensity of the ultra-violet light and the proportion of visible light in the total radiation begins to fall again.

We considered above laws governing radiation from an absolutely black body. However, in order to make a quantitative assessment of the source of light radiation in an atomic explosion on the basis of these laws, we have to know the temperature, radius and glowing time of the luminous region of the atomic explosion.

As pointed out above, when an atomic charge is exploded in the air, a luminous region shaped like a sphere is formed and acquires a diameter up to several hundred meters or more with time, according to the caliber of the nuclear charge. As the region increases, the temperature of its surface falls. The approximate variation in temperature and radius of a fireball with time in the case of a charge with a TNT equivalent of 20,000 tons is shown in Fig. 46. The time in seconds is plotted along the horizontal axis, and along the vertical axis we have, on the right the radius of the fireball in meters, and on the left its temperature of the surface. It is clear from this graph that about one hundredth of a second after the explosion, the temperature of the surface of the fireball drops to 2000°K. After that it increases again, and after 0.2 - 0.3 seconds is approximately 8000°K, after which it slowly drops again. In order to explain this variation in temperature, let us consider in greater detail the process of formation and development of the fireball.
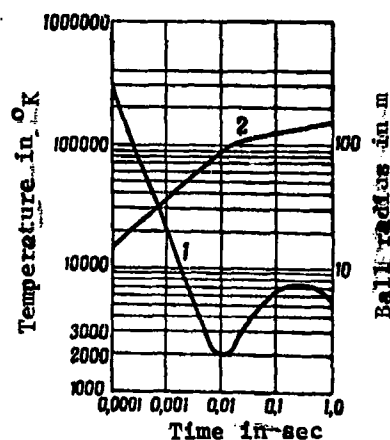
Fig. 46. Variation in temperature (1) and radius (2) of a fireball with time.

As has already been pointed out, when a nuclear charge explodes, the tempeature at the point of explosions attains millions of degrees. At /this fantastic tempeature, the part of the charge which has not had time to split, the casing and all the other parts of the bomb are evaporated. The temperature of the vapor is also extremely high. It emits radiation with a spectrum covering a wide waveband

-121-

stretching from long-wave, infra-red light through the visible and ultra-violet spectrum to x-rays. But the bulk of the radiation consists of soft x-rays which are absorbed by the air layers directly adjacent to the bomb, causing the air to become white hot. Air begins to glow (given the presence of nitric oxides and other impurities formed during the explosion) as soon as its temperature reaches about 2000°K. When the temperature is raised further, the air itself begins to radiate, the radiation being absorbed by the cooler air layers.

At a temperature of 30,000°, for example, air begins to emit radiation which is mainly absorbed by the cool air layers. Hence the radiation emitted by the incandescent explosion products excessively heats up more and more layers of air. This process takes place so quickly that in several microseconds a luminous area in the shape of a ball is formed at the point of the explosion, the ball consisting of the incandescent explosion products and air. The molecules of these substances are split up into atoms, and the atoms are ionized. After 0.0001 sec the radius of the fireball is about 15 m, and the temperature of its surface is about 300,000°K. The temperature is almost the same at all points inside the fireball, right up to the outside surface, since the energy may spread very quickly between any two points inside the sphere. A ball with the same temperature at all points is called a homothermal ball. The gas pressure at the surface differs sharply from the pressure and density of the surrounding air. This makes the fireball expand at a velocity slightly greater than the speed of sound (340 m/sec) compressing the adjacent air. The compression of the first air layer is transmitted to the second and this is the beginning of the air shockwave.

At the initial moment of formation of the fireball the rate at which the layers of air heat up and the velocity of the shockwave front are equal, so that the wave front coincides with the surface of the homothermal ball. When the temperature of the surface has dropped to 300,000°K, the velocity of the wave front is greater than the rate of heat-up of the air layers. The shockwave front moves in front of the homothermal ball surface[1]. But the temperature at the shockwave front due to compression, although lower than the temperature in the homothermal

region is nevertheless sufficient for the air to become incandescent.

I)

A simplified explanation of this effect is as follows:

Because of the high temperature of the fireball, most of the radiation (about 70%) occurs in the ultra-violet spectrum, in which the wavelengths are less than 0.186 microns. This radiation is greatly absorbed by the air, since the mean free path of a photon is 0.01 cm or less.

As an average each photon moves at the speed of light over a distance equal to the mean free path. It is then absorbed by an atom, molecule or gas ion, usually nitrogen or oxygen, present in the air, which are then transformed into the excited state. When the atoms return to the normal state, they radiate a new photon. This photon continues to move at random at the speed of light, but is then captured by an atom or molecule of air, after which it emits a photon, and so on.

On account of the low mean free path of radiation with wavelengths less than 0.186 microns, as well as the alternation of absorption and emission, the total rate of transfer of the radiation is relatively low. That is why the shock-wave front spreads more rapidly than the isothermal sphere .

It should be kept in mind that this slow transfer only relates to very short wave radiation (less than 0.186 microns). Rays from the neighboring ultra-violet and visible infra-red bands on the spectrum move great distances away from the fireball at the speed of light.

Thus, after about 0.0001 sec the homothermal ball is surrounded by a rapidly increasing layer of luminous, though less incandescent air formed by the shockwave front. On account of the fact that the shockwave front is luminous, it is not only a source of light radiation, but also strongly obserbs the radiation passing through it, in other words it acts as a kind of screen filtering some of the energy from the hotter homothermal ball. This is also aided by the nitric oxides formed at the wave front when the air heats up to a high temperature. For example, several foreign sources point out that when an atomic bomb with a TNT equivalent of 20,000 tons is exploded, about 100 tons of nitrogen dioxide is formed (a brown gas). Nitric oxides are opaque to visible rays.

As the shockwave front spreads, the pressure and temperature in it drop and the moment eventually arrives when the pressure and temperature drop so low that the air stops glowing. This takes about 0.01 sec and is represented by the minimum on the curve in Fig. 46, that is to say, a temperat ure at the front of 2000°K. The interval between the explosion and the moment of time 0.01 sec is termed the first period of development of the fireball. What happens next, when the shockwave front stops being luminous? At that moment there begins the second stage of development of the luminous region. Since the air at the front of the shockwave cannot now radiate, or absorb radiation, it gradually becomes transparent. The front of the shockwave therefore ceases to be a screen for the radiation from the inner, hotter middle region (of the ball), which now becomes visible and attains a radius of about 100 m. The temperature of the surface of the fireball, having obtained the minimum, begins to reascend until it reaches the temperature of the homothermal ball. This leads in time to the formation of a maximum in the tempeature of the adiating surface e qual to 7000-8000°K. Having attained this point, the temperature of the surface of the luminous region at about 0.2 - 0.3 sec begins to drop again on account of energy loss on radiation and cooling the incandescent gases from the fireball through expansion. At this second stage of development of the fireball its size increases through gas dynamic expansion. Approximately one second after the beginning of the explosion, the temperature of

-124-

fireball has dropped to 5000°K while its size is almost maximum: its radius is about 150 m.

The fireball continues to incandess for about 3 seconds. By this time its radius has attained 200 m or more. (all these data refer to a charge with a TNT equivalent of 20,000 tons).

When charges of greater caliber are exploded in the air, including hydrogen bombs, there is also a luminous region in the form of a ball, but its size and the glow time are greater than for an atomic bomb with a TNT equivalent of 20,000 tons. The form of curves showing the fireball temperature and size are similar to those in Fig. 46, but the time scale is different.

The following relationship between the diameter of the fireball and the TNT equivalent of the nuclear charge has been quoted in foreign literature[1], Table 3.

Table 3.

Dimensions of fireball as function of TNT equivalent of nuclear charge

TNT equivalent, tons	1 тыс.	20 тыс.	1 млн.	5 млн.	10 млн.
Diameter of fireball, m	110	360	1770	3120	4260

As follows from this table, it can be assumed for rough calculations that the radius and glow time of the fireball are proportional to the cubic root of the TNT equivalent of the charge. Consequently, if we know the maximum radius (let us assume for the sake of simplicity that it is 200 m) and the glow time (3 sec) for an atomic bomb with a TNT equivalent of 20,000 tons, we can find the radius and glow time of the fireball of an atomic bomb of any other caliber. Let us calculate, for example, these values for a bomb five times more powerful, possessing a TNT equivalent of 100,000 tons. Taking the cubic root of the ratio of the TNT equivalents ($\sqrt[3]{5}$), we get 1.71. By increasing the radius and glow time of a fireball from a bomb with a 20,000 ton equivalence by this number of times, we find the radius and glow time for a bomb five times more powerful (100,000 tons).

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-125-

They are equal: the radius is about 340 m and the glow time approximately 5 sec.

Thus, during atomic and hydrogen explosions the source of light radiation is the luminous sphere shaped like a ball (hemisphere) with a surface temperature varying with time. The size of the ball also varies with time, and its maximum depends on the TNT equivalent.

Let us now determine the total energy radiated by the fireball into surrounding space.

Total energy radiated by a fireball. It is not difficult to make a quantitative assessment of the radiation from any luminous body obeying the laws governing the radiation of an absolutely black body provided we know the temperature and size of the surface of the body, as well as the glowing time. It is especially easy to do this if the temperature AND size of the surface remain unchanged while emitting light.

The total energy radiated by the fireball is then the product of the intensity of radiation and the area of the ball surface plus the glow time. In this case, however, both change with time after the explosion. Here the calculation can be made by two methods. Under the first method we assume the size and temperature of the fireball to be mean constants; the total energy is then found in the way we have just mentioned. In the second method the calculation is made for separate short intervals of time, over which the temperature and area of the surface can be considered constant. To determine the total energy radiated by the fireball over the total time we add the radiation energies found for separate time intervals.

As an illustration let us calculate the total energy radiated by a fireball during the explosion of an nuclear charge with a TNT equivalent of 20,000 tons using the second method. On the basis of the graphs showing the variation in temperature and radius of the fireball with time in Fig. 46, and using the first law of radiation from an absolutely black body, we can plot a curve for the luminous energy radiated by the entire surface in time. The curve is shown in Fig. 47.

-126-

Along the horizontal axis we plot the time in seconds and along the vertical axis the amount of luminous energy radiated by the entire surface of the fireball each given moment of time. The area contained by the curve and the horizontal axis gives the total amount of luminous energy radiated by the fireball while it is incandescent. In the case of the explosion of an atomic bomb with a TNT equivalent of 20,000 tons this amount of energy is about 7 billion kilocalories, that is to say slightly more than 1/3 of the total energy released during the explosion. Furthermore, on the basis of this curve we can easily calculate the amount of energy radiated by the fireball at any moment of time t. To do this we have to calculate the area beneath the curve in the segment along the time axis from zero to the given moment t. This calculation enables us to find out what percentage of the given energy is d-excited by the given moment, as well as the time over which the basic luminous energy is radiated by the fireball; we have to know this in order to organize anti-atomic defense properly.
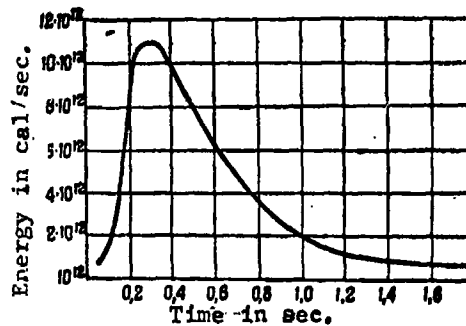
Fig. 47. Variation in energy radiated by total surface of fireball with time.

The calculations carried out in this way (on the basis of the curve in Fig. 47) are shown in Fig. 48. They enable us to ascertain the following important conclusions:

1) Despite the fact that at the first moment of time after the explosion (up to $t = 0.01$ sec is considered the first stage of development of the fireball) the temperature of the surface is very high, while the proportion of luminous energy radiated over this time with respect to the total amount of

luminous energy radiated over the whole period of incandescence is small and amounts to approximately 1%. This is due to the brevity of the first stage of development of the fireball.

2) Practically all the luminous energy during a nuclear explosion is radiated by the fireball at the next (second) stage of development, and in the case of intermediate bombs the bulk (80 - 85%) of this energy is radiated during the first second after the explosion, while the remainder (20 - 15%) is radiated within 1 to 3 seconds of the explosion.
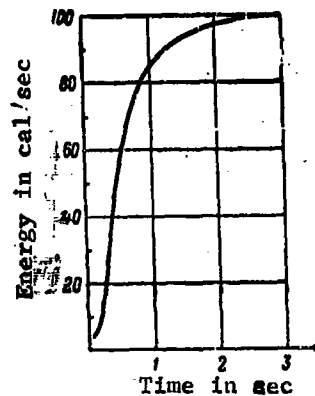
Fig. 48. Proportion of luminous energy de-excited by different moments of time during explosion of a bomb with TNT equivalent of 20,000 tons.

Luminous radiation spectrum during nuclear explosion. It was established in the preceeding section that practically all (99%) of the luminous energy in an atomic explosion is radiated between $t = 0.01$ sec and $t = 3$ sec after the explosion, and 80 - 85% is radiated between $t = 0.01$ sec and $t = 1$ sec after the explosion. On the basis of the graph shown in Fig. 46 we can easily find out the temperature of the surface of the fireball during this period. The temperatures range from $2000°K$ to $7000 - 8000°K$. But if we know the temperature of the surface of the ball, then wex can use Planck's formula to determine the energy distribution over the spectrum.

Fig. 49 shows the distribution of luminous energy over the spectrum at temperatures 2000°, 6000° and 8000°K.

-128-
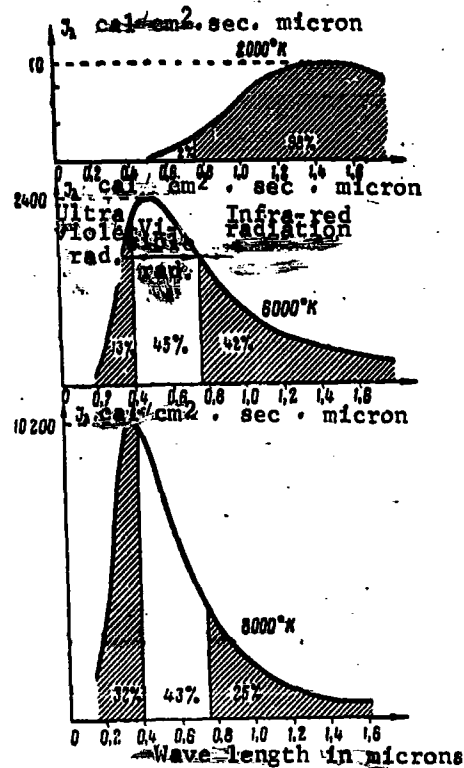
Fig. 49. Distribution of energy over spectrum for different temperatures
of fireball surface.

In these diagrams the horizontal axis shows the wavelengths in microns
and the vertical axis the amount of luminous energy emitted per second by 1 sq.
centimeter of surface (calculated per unit scale for wavelengths, that is to say
per one micron) i.e., the spectral intensity of radiation I_λ. The area bounded
by the horizontal axis and the curve shows the amount of luminous energy radiated
per second by one square centimeter of surface of fireball - the intensity of
radiation I_0.

The curves suggest the following: the higher the temperature of the
fireball surface, the greater the amount of luminous energy radiated in the ultra-
violet region. As an illustration Table 4 shows the ratio (calculated from Fig. 49)
between the energies of different parts of the light spectrum at different tem-
peratures of the surface of the wall.

Table 4

Distribution of luminous energy as function of surface temperature
of fireball

Surface Temperature °C.	Ultra-violet radiation	Visible radiation	Infra-red radiation
2000	None	2%	98%
4000	2%	28%	70%
6000	13%	45%	42%
8000	32%	43%	25%

It can be seen from the table that all three areas of the luminous
spectrum are present in the spectrum for the luminous radiation of a fireball
during an atomic explosion. But if it is taken into account that the temperature
of the surface when the bulk of the luminous radiation (80 - 85%) is emitted into
the surrounding medium is not greater than 8000°K, the spectrum contains mainly
visible and infra-red radiation.

But which regions of the spectrum are contained in the radiation from
a fireball during the first moments after the explosion (first stage of develop-
ment) when the surface temperature is measured in tens or even hundreds of
thousands of degrees? If we plot distribution curves on the basis of wavelength
for these temperatures, in the same way as was done in Fig. 49, it is found that
the bulk of the radiation falls to the lot of ultra-violet light, and this is
ultra-violet light with such long wavelengths (less than 0.186 microns) that it
is totally absorbed by the air round about. For example, even at a surface
temperature in the luminous region of 30,000°K, the amount of energy in these
rays comprises about 70%, while the remaining 30% is converted into ultra-violet
light(with wavelength greater than 0.186 microns) and the visible region of the
spectrum. Beginning at the surface temperature of 50,000°K or more, almost all
the radiation is longer in wavelength than 0.186 microns, that is to say it is
practically all absorbed by the air. The remaining regions of the spectrum only
get a small share, and the higher the temperature of the surface, the smaller this
share is. Thus, at the first stage of development of the fireball, all the
radiation is ultra-violet light, absorbed by the air.

At the end of one second after the explosion of an intermediate nuclear charge, the fireball is still emitting about 15 - 20% of the total luminous energy. Since the temperature of the surface of the ball does not exceed 5000°K during this time, the bulk of the luminous energy falls in the infra-red region of the spectrum.

Thus, at the earlier (first) stage of development of the luminous region, the shortwave ultra-violet portion of the luminous energy may predominate in the spectrum, but in magnitude it cannot exceed 1% of the total luminous energy emitted. Conversely, the bulk of the luminous energy from a nuclear explosion is radiated at the later (second) stage and the visible and infra-red regions of the spectrum now predominate. It should be pointed out that as an average the luminous radiation spectrum produced by an atomic explosion is reminescent of the solar spectrum.

2. Light pulses

The basic characteristic of the destructive effect of luminous radiation from a nuclear explosion is the amount of luminous energy incident on one square centimeter of illuminated surface perpendicular to the direction of radiation over the entire period of incandescence of the fireball. This amount of luminous energy is known as the light pulse. The magnitude of the light pulse depends:

a) on the amount of luminous energy radiated by the fireball during the entire period of incandescence E; since the luminous radiation is a definite part (1/3) of the total energy released during an atomic explosion, the magnitude of the light impulse is therefore dependent on the caliber of the bomb;

b) on the distance between the illuminated surface and the center of the nuclear explosion;

c) on the state of the atmosphere at the moment of explosion;

d) on the type of explosion (ground-level or in the air). The luminous radiation from the luminous region spreads in a straight line. If we describe a

-131-

circle with radius $\underline{R}$ around the luminous region of an aerial atomic explosion, the energy radiated by this region throughout the incandescent period, providing the energy is not weakened in the atmosphere, will pass entirely through the surface of the circle which is

$$S = 4\pi R^2 \ \text{cm}^2$$

This means that the energy per 1 cm^2 of this surface is

$$U = \frac{E_{\text{лиз}}}{4\pi R^2} \ \text{cal/cm}^2$$

This amount of energy is conventionally termed the light pulse.

The light pulse in this case is expressed in calories per square centimeter.

As can be seen from the equation, the light pulse is inversely proportional to the square of the distance from the center of the explosion, if the atmosphere is fairly transparent. As the distance is doubled, the pulse is reduced by a factor of four through expansion of the luminous flux, and if the distance is trebled, it is reduced nine times.

If the atmosphere did not weaken the luminous radiation (while the latter passed through it), calculation of the light pulse at any distance from the center of the explosion would be extremely simple. Let us assume that we want to find out the light pulse for an atomic bomb with a TNT equivalent of 20,000 tons at distances of 1, 2 and 3 km. To find the pulses at these distances, we substitute into the light pulse equation, instead of the energy, the value $7 \cdot 10^{12}$ cal, and instead of the square of the distance, the figures 10^{10}, $4 \cdot 10^{10}$, $9 \cdot 10^{10}$, successively (the squares of the distances in cm). Then we get the following values for the light pulses: 56 cal/cm^2 at 1 km; 14 cal/cm^2 at 2 km; 6.2 cal/cm^2 at 3 km. These are what the light pulses would be, were not the luminous energy weakened by the atmosphere. In practice, however, the energy is *ALWAYS* weakened to some degree or other as it passes through the atmosphere. Let us consider this case in greater detail.

-132-

3. Weakening of luminous radiation during passage through atmosphere

The gaseous layer surrounding the earth is called the atmosphere. It is a complex mixture with a virtually unchanging composition of basic gases (nitrogen, oxygen, argon and carbon dioxide), but with a varying quantity of different impurities. Among these are water (in the liquid or solid state) dust, smoke, soot and WASTE gases from industrial plants. The amount of impurity in the atmosphere, particularly in the layer of air adjoining the earth, depends on the locality, season and the day. For example, mist is usually found in coastal regions and over large reservoirs. Dust is usually found in the desert during the dry season. There is a great deal of smoke, soot and dust in nearby industrial plants.

The presence of these impurities in the atmosphere weakens the light radiation as it passes through it.

What does the weakening of the luminous radiation mean? As it passes through the atmosphere it is partially scattered and partially absorbed.

The scatter is the variation in rectilinear direction of the light by particles present in the atmosphere. These particles are molecules of gases making up the air, mist drops, dust particles, and so forth.

Scatter is a very complex effect. As the light ray meets a particle in its path, it is reflected from it, strikes another particle and is reflected a second time. The doubly reflected ray then hits a new particle and is reflected a third time, and so on and so on.

Motorists are well acquainted with scatter; when a car with its headlights on drives through mist the beams of light lose their direction on account of scatter caused by the little drops of water and become broader. If the mist is fairly thick, the driver sees a dazzling patch of LIGHT instead of a beam.

The greater the dust, smoke and water content of the air, the greater

scatter there is.

The effect of scatter imposes certain obligations on the installations used for protection from an atomic explosion.

For example, trenches must have covered areas, since people in open trenches may be injured by the scattered luminous radiation. Furthermore, the scattered luminous radiation causes temporary blindness, even if the victims are not looking in the direction of the explosion.

Apart from scatter, luminous radiation is also absorbed by particles of dust, water vapor, oxygen molecules, carbon dioxide and ozone when it passes through the atmosphere. The absorbed luminous energy changes into heat and warms up the air. Many absorption bands in different parts of the spectrum due to the passage of luminous radiation through the atmosphere are known. This suggests the following:

a) Ultra-violet radiation with wavelength less than 0.186 microns is totally absorbed by the oxygen in the air (the oxygen only needs to be 1 m thick).

Consequently, there are no ultra-violet rays with wavelengths less than 0.186 microns in the luminous radiation spectrum from a nuclear explosion.

b) Ultra-violet radiation with a wavelength less than 0.29 microns is strongly absorbed by ozone (triatomic oxygen - O_3). For example, there is no ultra-violet radiation with a wavelength less than 0.29 microns in the solar spectrum at the surface of the earth, since it is totally absorbed by the ozone in the upper layers of the atmosphere. This produces a particularly warm layer in the atmosphere (according to certain data, temperature is about +35°) at heights of 40 - 55 km, where the ultra-violet light begins to enter the ozone layer.

Let us take a brief look at the question, to what degree is the luminous radiation from the explosion absorbed by ozone?

It can be said for certain that very little light radiation from the atomic explosion is absorbed by the atmospheric ozone. But during an atomic explosion a large amount of ozone is created by the effect of gamma rays, x-rays

-134 -

and ultra-violet light on the oxygen in the air (wavelengths ranging from 0.13 to 0.175 microns). When these rays act on a molecule of oxygen, it splits up into oxygen atoms which combine with other oxygen molecules and form ozone. The ozone is partially destroyed by the high temperature. It is partially spent on oxidizing the organic matter which is always present in the atmosphere in the form of dust (a particularly large amount is thrown up by an atomic explosion), and is partially destroyed by collision with oxygen atoms. A great deal of the ozone goes into absorption of the ultra-violet radiation with wavelengths less than 0.2 microns. Absorption bands due to ozone are also observed in the infra-red region of the spectrum. For the moment there is no definitive data on the absorption of ultra-violet light from an atomic explosion by ozone. Foreign literature contains only fragmentary information[1], according to which measurements at distances greater than 9 - 16 km from the center of the atomic explosion reveal no sign at all of radiation with wavelengths less than 0.3 microns. This is confirmed by experiments (described in foreign literature) with animals irradiated during an atomic explosion through filters eliminating the entire spectrum except for ultra-violet light. No BURNS were caused through the ultra-violet rays. It was established by these results that burns obtained through filters which only allow through visible or only infra-red light were no different in intensity (all other things being equal), although in certain cases burns due to visible light were more serious. This means that in an atomic explosion the harmful effect of luminous radiation is basically due to visible and infra-red rays.

c) There are many absorption bands in the infra-red region which are basically due to water vapor and carbon dioxide.

In order to make allowance for the weakening of the light radiation during its passage through the atmosphere, we add a correction multiple $e^{-k(R-r)}$ to the equation for the light pulse; this multiple takes into account weakening

1) "The Effects of Atomic Weapons", New York-London, 1950.

over the path (R-r). Here R is the distance between the center of the luminous region and the point at which the radiation is measured, and r is the radius of the luminous region. If R and r are expressed in kilometers, the final equation for calculating the light pulse at a distance R from the center of the explosion, making allowance for weakening of the light radiation by the atmosphere, is

$$U = \frac{E_{лл}}{4\pi \cdot 10^{10} \cdot R^2} \, e^{-k(R-r)} \quad \text{cal/cm}^2$$

where $E_{лл}$ is the total luminous radiation energy in calories;

R   is the distance between the center of the explosion in kilometers;

r   is the mean radius of the luminous region in kilometers;

k   is the mean weakening factor of the radiation for the entire wave band with the dimensionality 1/km;

e   is the natural logarithm base equal to roughly 2.72;

π = 3.14.

The equation can be simplified for practical purposes. Taking it into account that 1/3 of the explosion energy is spent on luminous radiation, the equation for the light pulse takes the form

$$U = \frac{2.65 \cdot 10^{-3} \cdot q}{R^2} \, e^{-k(R-r)} \quad \text{cal/cm}^2$$

where q is the TNT equivalent of the explosion in tons;

R is the distance from the center of the explosion in kilometers.

The other quantities are the same as before.

The weakening (attenuation) factor for the effect of the atmosphere on the luminous radiation has been studied for a narrow beam of rays (for when the ray leaving the beam through scatter does not go back to it). But during an (aerial) atomic explosion luminous radiation is emitted from the luminous region in all directions, that is to say at a solid angle of 4π, which embraces most of the narrow beams of light rays. In this case the scattered portion of radiation from one beam of light is augmented by the scatter from another beam.

If the atomic explosion occurs in a homogeneous medium (one with uniform density), all the photons emitted by the luminous region, with the exception

-136-

of those absorbed by the medium, will pass through a sphere of arbitrary radius described around the center of the explosion. The weakening of the luminous radiation will then be determined solely by absorption.

In actual fact, the point of explosion is not surrounded by a homogeneous atmosphere; the concentration of scattering centers above this point decreases, as a rule, with the increase in altitude. Furthermore, the atmosphere is limited below by the surface of the earth. We are more interested in the weakening of the radiant energy in a horizontal direction. The reduction in concentration of the scatter centers with altitude suggests that the atmosphere is more transparent vertically than horizontally. A luminous flux spreading horizontally passes through a denser medium than when travelling vertically, and therefore loses MORE SCATTER than it acquires. Furthermore, a great deal of radiant energy striking the ground is absorbed. Thus, scatter also leads to attenuation of a luminous flux. The luminous radiation spreading horizontally from the luminous region is decreased through scatter in an upward direction and through absorption by the earth.

This is a brief qualitative picture of the weakening of the luminous radiation from an atomic explosion when it passes through the atmosphere.

A quantitative assessment of this effect when luminous radiation passes through the atmosphere is extremely complicated. A rough evaluation of the attenuation factor for the luminous radiation from a nuclear explosion $\underline{k}$ for different states of the atmosphere may be made, according to the foreign press, on the basis of the graph shown in Fig. 50. The state of the atmosphere is usually described by the meteorological visibility, which is taken to mean the maximum distance at which large dark objects, such as trees, dark houses, buildings, etc., can be made out in the daytime against the skyline.

It is not difficult to see from the graph that the attenuation factor ranges from zero for exceptionally clear atmosphere to $\underline{k} = 2\frac{1}{km}$ in fog.

The visibility of a town averages about 10 km, and then $k = 0.4\frac{1}{km}$.

-137-

It is difficult for the moment to say how close to the truth the data in Fig. 50 are. Further investigation is needed to verify them.

In clear weather the absorption of luminous radiation by the atmosphere can be virtually disregarded. Hence if it is necessary to produce the greatest radius of damage due to light radiation, the enemy will aim at using his atomic weapons when the visibility is good. This should be taken into account when organizing anti-nuclear defense.

Smoke screens can be used to weaken the luminous radiation and provide protection. Smokescreens are basically intended for camouflaging the deployment and movements of troops and military objectives, and to blind the enemy's artillery sites, observation points and dislocations. As is well known, smokescreens are thick fogs/ PRODUCED ARTIFICIALLY In the atmosphere by so-called smoke-producing materials. In an atomic explosion smokescreens can weaken luminous radiation in the same way as natural mist. Within certain limits the attenuation factor is directly proportional to the concentration by weight of smoke in mg/l or g/m^3.

The proportion of energy of absorbed light in the total loss of luminous energy through scatter and absorption is a function of the size of the smoke particles, the wavelength of the light and the refractive index of the particles.

In the case of uncolored smoke, from 10 to 30% of the total loss of luminous energy through radiation and absorption is used on absorption, but in the case of black smoke, the figure rises to 80%. It can be concluded from this that if a smokescreen is set up, the harmful effect of the luminous radiation can be reduced to a certain extent.

It is pointed out in the foreign press that a thick smokescreen between the point of the explosion and the target may reduce the light pulse by a factor of 10, compared with the pulse which would have been produced without the smokescreeen. So smokescreens can evidently weaken the effect of the luminous radiation from a nuclear explosion.

Light pulses when luminous radiation is weakened by the atmosphere. On the basis of what has been said above we can evaluate the light pulses at different distances from the center of the nuclear explosion under different atmospheric conditions.

For an aerial explosion (altitude of explosion H = 600 m) of a TNT equivalent of 20,000 tons, the light pulses calculated by the equation given in the preceeding section are shown in Fig. 51. In this graph the horizontal axis shows the distances from the epicenter[1] of the nuclear explosion in kilometers, and the vertical axis plots the light pulses in cal/cm^2.

Each curve is calculated for a certain attenuation factor k.

The curves in Fig. 51 show that the greater k, the less the light pulse for the same distance. For example, at 1.5 km from the epicenter of a nuclear explosion when the luminous energy is not weakened at all by the atmosphere, the light pulse is 30 cal/cm^2. For the same distance when the attenuation factor is $k = 0.2$ (1/km), the light pulse is 15 cal/cm^2, and when the attenuation factor is $k = 2$ (1/km), the light pulse is only 1 cal/cm^2.

It is also easy to see that the luminous radiation from a nuclear explosion as a destructive factor is a function of the state of the atmosphere at the moment of the atomic explosion. During fog, rain or snow the destruction caused by the luminous radiation occurs at shorter distances than in good weather. This is a feature of the luminous radiation as a destructive factor, compared with other such factors (shockwave, penetrating radiation and radioactive contamination) in an atomic explosion. Conversely, the radioactive contamination of

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[1] In the case of an aerial explosion the light pulses at different distances from the epicenter of the explosion can be found from the same equation, provided for R we substitute $\sqrt{R_e^2 + H^2}$, where R_e is the distance from the epicenter and H is the height of the explosion.

Attenuation coefficient to km
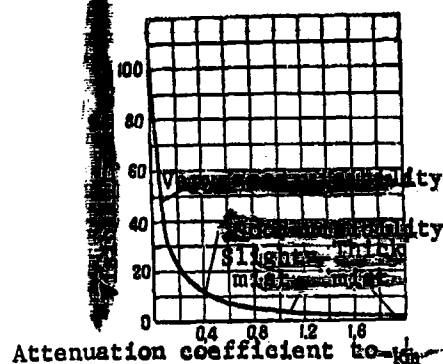
Fig. 50. Attenuation factor as function of visibility.
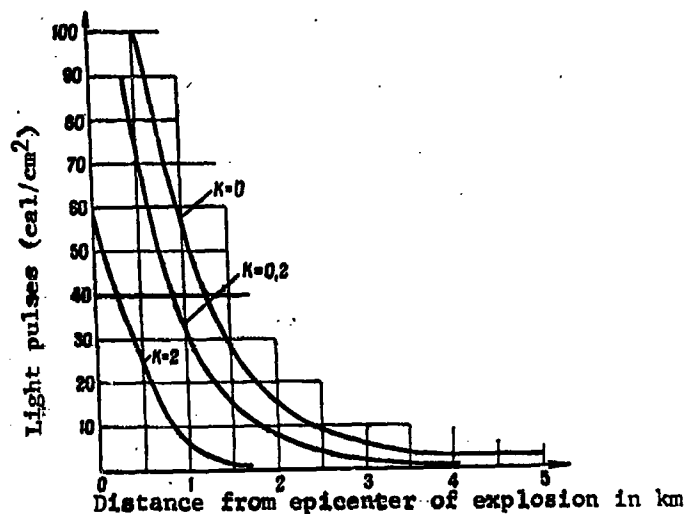
Fig. 51. Variation in light pulses with distance from epicenter of explosion

for different attenuation factors during explosion of an atomic bomb

with a TNT equivalent of 20,000 tons.

locality in an aerial explosion when there is mist, rain or snow, may be considerably increased. But it must not be forgotten that in very good weather on open terrain during the aerial explosion of a nuclear bomb with a 20,000 ton TNT equivalent, the shockwave and penetrating radiation injure people up to 2000 m from the epicenter. The light radiation may cause burns on uncovered parts of the body at distances up to 4000 m.

In conclusion, we should say a few words on the shape of the light pulse. The shape of the pulse is the dependence (in particular, in terms of a graph) between the intensity of illumination and the time. Above we quoted the light

-140-

pulses, that is to say, the amount of energy incident on 1 cm of body surface
(perpendicular to the incident rays) throughout the period of luminescence of
the fireball. In practice we sometimes have to know the intensity of the energy
travelling a certain distance from the center of the explosion (intensity of
illumination). It can easily be calculated on the basis of the curve given in
Fig. 47, and the equation for the light pulse. The dependence of the intensity
of illumination on the time at 2 kilometers from the center of a nuclear ex-
plosion (shape of the pulse) for two states of the atmosphere is shown in Fig. 52.
The area contained between each curve and the horizontal axis obviously shows the
light pulse at a set distance from the center for a given state of the atmosphere.

Light pulse as function of nuclear caliber of charge. The light
pulses given above related to nuclear charges with a 20,000 ton TNT equivalent.
The equation can easily be used to calculate the light pulses at different
distances from the center or epicenter of a nuclear explosion for any other TNT
equivalent and for any state of the atmosphere. As an illustration, Table 5
shows the light pulses (calculated from this equation) for different distances
from the epicenter of an aerial explosion for two atomic bombs with a TNT equiva-
lent of 20,000 and 100,000 tons. The pulses are calculated for three states of
the atmosphere with attenuation factors $\underline{k} = 0$, $\underline{k} = 0.08$ and $\underline{k} = 0.2$ (1/km).
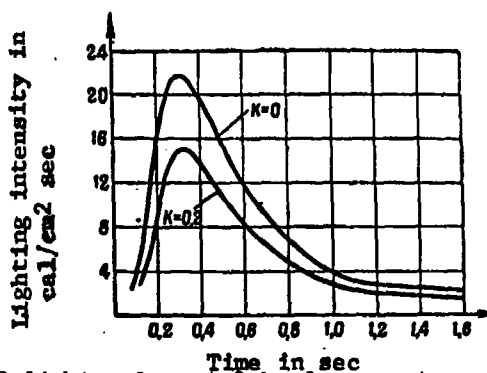
Fig. 52. Shape of light pulse at 2 km from center of explosion for two states
of the atmosphere with attenuation factors $\underline{k} = 0$ (no weakening) and
$\underline{k} = 0.2$ (1/km) (visibility 20 km).

-141-

As follows from the light pulse equation, if we know the light pulse U_1 at a distance for a charge with the TNT equivalent q_1, we can find the light pulse U_2 at this distance for the charge with the TNT equivalent q_2. In a case in which weakening of the luminous radiation in the atmosphere can be disregarded, the equation for the pulse U_2 takes the form

$$U_2 = U_1 \frac{q_2}{q_1},$$

Table 5.

Light pulses at different distances from center of
aerial nuclear explosion

Distance from center of explosion, km	Nuclear charge equivalent to 20,000 of TNT			Nuclear charge equivalent to 100,000 of TNT		
	$\varkappa = 0$	$\varkappa = 0,06$	$\varkappa = 0,2$	$\varkappa = 0$	$\varkappa = 0,06$	$\varkappa = 0,2$
1	55,0	53,0	47,0	280,0	260,0	240,0
2	14,0	12,0	9,6	70,0	61,0	49,0
3	6,2	4,8	3,5	31,0	25,0	18,0
4	3,5	2,6	1,6	17,2	13,0	8,3
5	2,2	1,5	—	11,0	7,6	4,3
6	—	—	—	7,7	4,9	2,5
7	—	—	—	5,7	3,3	1,5
8	—	—	—	4,3	2,4	—
9	—	—	—	3,1	—	—
10	—	—	—	2,6	—	—
11	—	—	—	2,3	—	—
12	—	—	—	1,9	—	—

Let us illustrate the use of this equation. At 2 km from the center of the explosion the light pulse for a charge with a TNT equivalent q_1 = 20,000 tons is U_1 = 14 cal/cm^2. The light pulse for the same distance for an explosion with a TNT equivalent q_2 = 100,000 tons, on the basis of the equation is

$$U_2 = 14 \frac{100\,000}{20\,000} = 70 \text{ cal/cm}^2$$

Light pulse in cloudy weather. It was shown above that when there is mist, rain or snow the light pulse may be less than in good weather, because of the weakening of the luminous radiation. The situation is quite different when an atomic bomb is exploded in cloudy weather. Let us imagine that there are dense clouds not very high above the earth and that the atomic explosion occurs between the ground and the clouds. In this case the light pulses received by objectives at different distances from the epicenter of the explosion will be greater than those produced in clear weather. This is because the luminous radiation emitted by the fireball in an upward direction is partially reflected from the clouds and

-142-

returns to earth (Fig. 53). Furthermore, the luminous radiation emitted by the fireball towards the ground helps to increase the luminous pulse. When it reaches the ground, the luminous radiation is partially reflected, goes back to the clouds, is reflected by them and returns to the earth again. For the given distance from the epicenter of the explosion, the degree of increase in the luminous pulse in cloudy weather depends on numerous factors: the height of the clouds above the ground, the thickness of them, the reflectivity of the ground, and so on.

The thickness of the clouds determines their ability to reflect the luminous radiation, and the thicker the cloud, the more of the incident luminous energy is reflected.
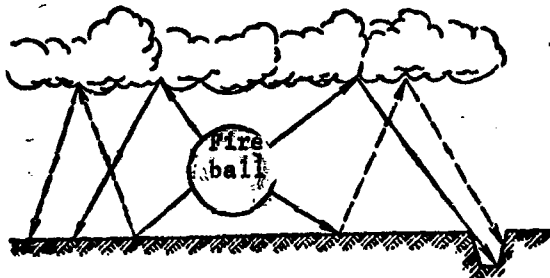
Fig. 53. Reflection of luminous radiation from clouds.

An approximate relationship between the reflection of the luminous radiation and the thickness of the cloud in percentage is shown in Fig. 54. It can be seen from the curve showing the approximate dependence of the reflection of luminous energy on the thickness of the cloud that when the cloud is 700 - 800 m thick, about 75 - 80% of the incident light radiation is reflected. The mean reflection factor for clouds, taking the different shapes and thicknesses into account, is about 50 - 55%. The presence of clouds during an atomic explosion thereby may require the use of further protective measures for buildings.

Indeed, persons taking shelter in open trenches may be burned by the luminous radiation reflected from the clouds (as is easy to see from Fig. 53), despite the fact that they are protected from the direct light rays. Calculation

-143-
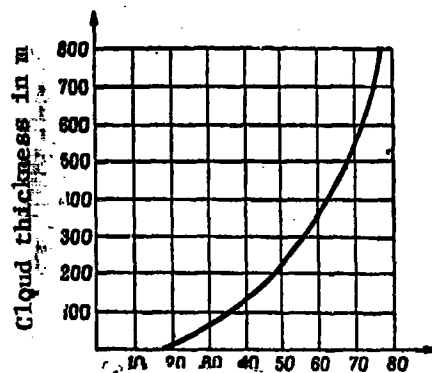
Reflection factor in % for stratus clouds

Fig. 54. Reflection factor as function of thickness of clouds.

suggest that in conditions in which the clouds and the surface of the ground

(for example, if covered by snow) reflect about 75 - 80% of the incident luminous

energy, the light pulse at certain distances from the epicenter of the explosion

(ratio of the height of the clouds above the ground to distance from the epi-

center of the explosion is 0.5 - 1.0) through reflection from the clouds and

ground alone may attain as much as half the light pulse created by the direct

light rays from the fireball.

This fact must be taken into account when organizing anti-atomic de-

fense.

On the basis of what has been said, installations for protection from

the light radiation as well as from the shockwave, penetrating radiation and radio-

active contamination must be covered over.

4. Destructive effect of luminous radiation from nuclear explosion

When the luminous energy U (light pulse) impinges upon a body after

emission from the fireball, it is partly reflected from the surface of the body

and partly absorbed, and partly transmitted through it, if the body is trans-

parent. The distribution of incident luminous energy is shown schematically in

Fig. 55. The solid arrow shows the incident luminous energy U, the wavy line with

the figure 1
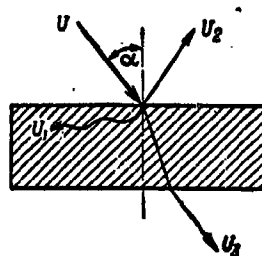
Fig. 55, Distribution of incident

light energy (light pulse);

U_1) absorbed by body; U_2) reflected;

U_3) passed through body.

shows the absorbed energy U_1, the reflected portion of luminous energy is shown as U_2, and the energy passing through the body is shown with the subscript 3. According to what has been said, we can easily write down the equality $U = U_1 + U_2 + U_3$. In the situation in hand, most bodies are almost entirely opaque ($U = 0$ with the exception of glass), hence it can be seen that some of the incident luminous energy is reflected from it while the remainder is absorbed by it, that is to say $U = U_1 + U_2$. We are interested in the portion of luminous energy absorbed by the body U_1. A body absorbing energy is heated up to a certain temperature. And according to the temperature to which it heats up, we find different forms of destruction - carbonization, ignition, fusion of materials or burns on the human body. Let us first consider how much incident light energy is absorbed by the body.

Absorption of luminous energy by different bodies. Different bodies absorb different amounts of the same incident luminous energy (the same light pulse). For example, bodies with dark surfaces absorb much more light energy than ones with white surfaces. In everyday life this property is widely applied: white summer suits, white paint used to coat refrigerator trucks, tanks and other installations where it is undesirable for the bodies to be heated by the sun's radiation. To describe the absorptivity and reflectivity of different bodies we usually use the absorption and reflection factors, which are designated, respectively, k_1 and k_2.

The absorption factor $k = (U_1 / U)$ is numerically equal to the ratio of the luminous energy absorbed by the body and the incident luminous energy. The absorption factor is a number showing how much of the light pulse is absorbed by the given body.

The reflection factor $k_2 = (U_2 / U)$ is numerically equal to the ratio of the luminous energy reflected by the body and the incident luminous energy. This factor is a number showing how much luminous energy is reflected by a given body. The absorption and reflection factors, as can be seen from their definitions, are

always less than unity. But according to the law of conservation of energy, the sum of them is always unity in the case of an opaque body; $k_1 + k_2 = 1$. This means that if we know one of them for a given body, we can find the other by subtracting from unity. For example, white paper has a reflection factor $k_2 = 0.80$, and an absorption factor $k_1 = 1-0.80 = 0.20$. The absorption and reflection factors are often expressed in percentage. Consequently, white paper absorbs 20% of the luminous energy on it. The absorption factor depends on the color of the body as well as the state of its surface. For example, a rough surface absorbs more luminous energy than a smooth or polished surface, a moist surface absorbs more than a dry one, and so on. But in addition to the state of the surface, the absorption coefficient also depends on the wavelength of the incident radiation.

Wave length in microns
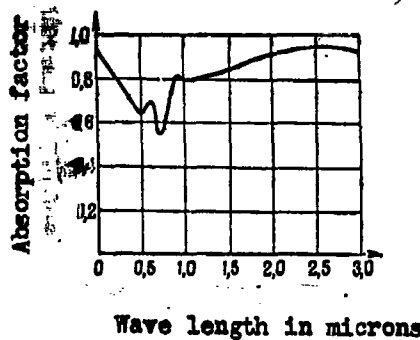
Fig. 56. Variation in spectrum of absorption factor of human skin on wavelengths of luminous radiation.

Fig. 56 shows an approximate variation in the absorption factor for human skin with the wavelength of the incident radiation. The graph shows this dependence for an average case. The wavelength of the light in microns is plotted along the horizontal axis and the absorption factor is plotted along the vertical axis. Over the many thousands of years that man has existed, his skin has BECOME well adapted to the sun's rays. Very little shortwave ultra-violet radiation reaches the surface of the earth, but it is nevertheless almost entirely absorbed by the skin, . only about 3% of the energy being reflected. Fig. 56 shows that in the visible region (wavelength from 0.4 to 0.8 microns) in which a great deal of solar energy is radiated, the skin absorbs very little: 65% of the energy is

-146-

absorbed, and 35% reflected. This weakens the radiation effect on the skin,
which otherwise be excessive. As the wavelength in the infra-red region is
increased, the solar energy is reduced and the absorption factor of the skin is
increased.

Human skin transmits different wavelengths to different extents. For
example, the ultra-violet region of the spectrum is totally absorbed by a layer
of skin several hundredths of a milimeter thick; as the wavelength is increased,
the transparency of the skin is also increased, attaining a maximum for infra-
red rays, 0.8 microns. For longer infra-red rays the transparency of the skin
is again reduced.

Fig. 57 shows the dependence of the reflection factor (absorption
factor) on wavelength for PLOUGHLAND and green foliage.
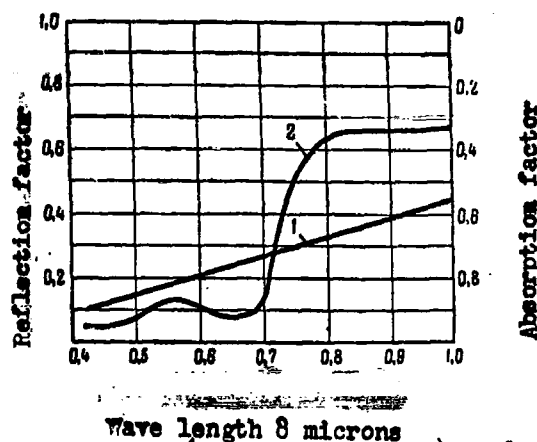
Wave length 8 microns
Fig. 57. Reflection factor (absorption factor) as function of wavelength
          of light for: 1) PLOUGHLAND ; 2) green foliage.

In view of the complex dependence of the absorption factor on wave-
length, use is usually made of mean absorption factors for all the three regions
of the light spectrum (ultra-violet, visible and infra-red). The mean absorption
factor can easily be calculated for any material if a curve like the one shown
in Figs. 56 and 57 is available. The question is made more complicated, how-
ever, by the fact that the intensity of the radiation differs in the case of
different wavelengths, in accordance with Planck's law. Hence, for every material
the mean reflection (absorption) factor for the spectrum is a function of the

spectral composition of the incident radiation, which is determined by the temperature of the light source.

As already pointed out, the mean spectrum for the luminous region of the explosion is close to spectrum of solar radiation. In practice, therefore, when evaluating the absorption capacity of the luminous radiation by different bodies, we use the reflection (absorption) factors for solar radiation.

On the basis of this, the mean absorption factor for human skin is 0.65, that is to say the skin absorbs about 65% of the incident light radiation (light pulse).

The following figures are averages: white paint 18%; black paint 96%; red and brown tile 70%; khaki cloth 60%; white cloth 25%; black cloth 99%; white paper 20%; dry grass dried up by the sun, cotton 80%, and so on.

The greater the absorption factor of the surface, the more luminous energy absorbed by the body, and the higher the temperature to which it heads up. The amount of luminous radiation which is absorbed by 1 cm of surface of an illuminated body is termed the heat pulse and is found from the equation

$$U_\tau = U \cdot \kappa_1 \cdot \cos \alpha,$$

where U_τ is the heat pulse in cal/cm^2;

U is the light pulse in cal/cm^2;

k_1 is the absorption factor;

α is the angle between the direction of propagation of the light and the perpendicular to the illuminated surface.

Thus, each body absorbs a different amount of luminous energy and this determines the degree of destruction it undergoes.

But does the destruction depend solely on the absorbed energy? It appears that some degree of destruction - ignition, carbonization, fusion of materials or burns on the body - depend to a great extent on other properties of the body as well, for example, its thermal conductivity, heat capacity and size (thickness).

-148-

But other factors also play a great part.

During a nuclear explosion the damage done to a body is largely conditioned by the amount of luminous energy, but it is also conditioned by the fact that this energy is released in a comparatively short period of time, calculable in seconds. The absorption of luminous radiation by bodies obviously occurs during this time. On account of the rapid supply of a large amount of heat to the surface of a body, only some of the heat can be transferred from the surface inside to the body by thermal conductivity or into the air by radiation and heat transfer. The temperature of the body surface is raised very high. The extent of the damage to the body depends on the temperature to which it is raised. If the emission (absorption) has the same amount of energy occurred over a longer period, the temperature of the surface would be much lower since a large amount of energy would be transferred from the surface inside the body to the thermal conductivity and the remainder would be radiated into the surrounding medium or would be transferred directly to the air. Hence there would be less damage or none at all, although the total amount of absorbed luminous energy would be the same. This can be shown clearly from the following example.

In one day each square centimeter of horizontal surface receives the following average amount of luminous radiation from the sun at different places in the Soviet Union: Irkutsk - 165 calories; Tbilisi - 206 calories; and Tashkent 278 calories.

If this amount of luminous energy fell on a square centimeter of surface during an atomic explosion (in three seconds), many substances would burst into flame, some metals would melt, and the uncovered parts of the human body would be charred. This does not happen, however, since the sun heats up the earth over a prolonged period. We can conclude from this that if the light pulse from two atomic bombs is the same, the degree of damage is comparatively less in the one whose period of luminescence is greater. Experience shows that the less the intensity of the lumination of a body surface, the greater amount of time is

-149-

required for illumination, that is to say the greater the light pulse required to inflict the same amount of damage. For example [1], if the intensity of illumination is 0.8 cal/cm^2 sec, cotton cloth ignites in 7 seconds; when the intensity is 1.0 cal/cm^2 sec, the cloth ignites in 5 seconds, and when the intensity is 1.3 cal/cm^2 sec, it bursts into flame within 3 seconds. This means that in the first case the light pulse is 5.6 cal/cm^2, in the second case 5 cal/cm^2 and in the third case 3.9 cal/cm^2. Since in the case of a hydrogen bomb the fireball continues to be luminous for a longer period than in an atomic explosion, the same light pulse produces less intensity of illumination in the case of the hydrogen bomb. Consequently, the same destruction is caused during an explosion of a hydrogen bomb when there is greater light pulse than during the atomic bomb explosion.

Let us now give the equations for determining the temperature of a body when acted on by luminous radiation from a nuclear explosion.

For thin metal sheets (roofs of houses, aircraft skins) it can be considered that the temperature is the same throughout. The rise in temperature due to the luminous radiation (compared with the initial temperature) is determined by the following equation, commonly used in textbooks on physics

$$\Delta T = \frac{U_\tau}{\gamma c \delta} \, {}^{\circ}C.$$

Here U_τ is the heat pulse in cal/cm^2;

γ is the specific weight of the material in g/cm^3;

c is the heat capacity of the material in cal/g deg;

δ is the thickness of the sheet in cm.

In the given equation the product $\gamma \cdot c = c_v$ is the volumetric heat capacity measured in cal/(cm^3 deg).

For thicker materials (armor plating on tanks, ships and other armaments) the material does not have time to heat through to the same extent during the comparatively brief period of illumination. The greatest temperature is found on

-150-

the illuminated surface. The rise in temperature of the outside surface by the end of the effect of the luminous radiation obeys the following law[2]

$$\Delta T = \frac{AU_t}{\sqrt{t}}.$$

Here A is the proportionality factor;

T_{ill} is the time taken by the luminous radiation to act.

This latter formula, incidentally, easily provides AN approximate relationship between the light pulse required to inflict a certain amount of damage on the given material in accordance with the caliber of the nuclear bomb. As can be seen from the equation, at the temperature of the surface (at which the material is damaged) the pulse is directly proportional to the square root of the illumination time t_{ill} (time over which the luminous radiation acts). As has already been pointed out, this time is approximately proportional to the square root of the bond caliber q. The light pulse U_1 required to do the same amount of damage to the material for a bomb of caliber q_2 is determined from the equation

$$U_2 = U_1 \sqrt{\frac{q_2}{q_1}},$$

where U_1 is the known light pulse required to do the same amount of damage for a bomb of caliber q_1.

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1)
    D. I. Lawson. Atomic bombs and conflagrations. Translation from English. Foreign Lit. Press, 1955.

2)
    "Nature" for 1949.

According to foreign press data (obtained during experiments), the approximate light pulses required to inflict the same amount of damage on different materials for two different atomic bombs - a 20,000 ton bomb and a one megaton bomb - are shown in Table 6.

The figures in parenthesis in the last column in the table are the light pulses calculated from the above formula. As we can see, the light pulses obtained experimentally and calculated from the equation tally well. Above we have considered the effect of thermal capacity, thermal conductivity, thickness of the body and illumination time on the extent of damage to a body.

Table 6

Light pulses causing damage to different materials

Material	Light pulse, cal/cm²	
	20,000 t	1 million t
Drapes (dark red color)	9	16(17.3)
Cotton cloth for blinds (white)	16	30(30.7)
Newsprint	3	6(5.8)
Pine shavings (light yellow)	5	12(9.6)
Dry rotting wood	4	9(7.7)
Falling leaves (dry)	6	12(11.5)
Thin grass (dry)	5	10(9.6)

Other factors such as the moisture content of the materials, their surface (whether painted or lacquered) and so forth have an effect on the extent of the damage. Generally speaking, it is very difficult to determine the conditions in which the material may be ignited or charred with any accuracy. The same thing can be said of skin burns. It is considered that when heat is rapidly supplied, as happens during an atomic explosion by absorption of the luminous radiation of high intensity, what determines the damage is the total luminous energy impinging upon a unit of illuminated surface, that is to say, the light pulse. The light pulses required to cause different degrees of damage have been determined experimentally for most materials. Some of them have been

given above, while others will be given in later sections.

In most cases the following general conclusions hold good. Dark colored cloth absorbs a greater degree of radiation than light colored cloth. Here, too, however, there are differences according to the method used to dye the cloth and the nature of the fiber. Wool is more radiation resistant than cotton or artificial fiber.

Less luminous energy is required to damage lighter materials than heavier ones. The energy required (given the same illumination time) is approximately proportional to the weight of the fabric per unit area. A greater light pulse is required to damage moist materials than dry ones.

Burns due to luminous radiation. The effect of luminous radiation on humans during a nuclear explosion is the appearance of burns of different degrees of severity. In practice there are two types of burns: burns directly due to luminous radiation, and burns by flame produced by the ignition of different materials by the luminous radiation. The latter type is characteristic of towns and populated points. These burns are caused by the fires which break out and also burning clothes. On open terrain (the battlefield) most burns would apparently be caused by the direct action of the luminous radiation. Burns from clothing or other materials which catch fire should not be ruled out, of course. Furthermore, there may be burns due to the dusty atmosphere heated up by the luminous radiation to a tremendous extent and set in motion by the shockwave.

According to foreign data[1], approximately 50% of all fatalities occurring as a result of the atomic bombing of Hiroshima and Nagasaki were due to burns of different types, 20 - 30% of which were caused by the luminous radiation directly, while the remainder were due to burns suffered through conflagrations.

Three quarters of all the casualties during the atomic explosions received burns. In Hiroshima, for example, 14,000 relatively serious cases of burns were reported. Leaving aside other possible injuries, luminous radiation

-153-

burns must have proved fatal in the case of almost all persons on open ground up to 1800 m or more from the epicenter of the explosion. Even between 3500 and 4200 m there were cases of burns which were very serious and required tre atment.

People on open ground received most of the burns due to luminous radiation. Nevertheless, there were many cases of burns among persons in buildings since most of the windows were open on account of the summer weather.

Most of the burns were due to the suddenness of the atomic attack, the lack of organized anti-atomic defense in the cities, the large amount of FLIMSEY wooden buildings and the lack of organized fire fighting to combat the fires which broke out.

A large percentage of the burns due to luminous radiation in Japan were undoubtedly connected with the warm, clear summer weather at the time of the explosion. In cold weather people would have been wearing thicker clothing and there would have been fewer burns.

Since fire burns are not typical of the injuries suffered by troops on the battlefield, we will not consider them any further here.

Let us consider in greater detail the burns directly due to the luminous radiation from an atomic explosion. In appearance these burns do not differ from ordinary fire burns. Luminous radiation first effects the uncovered parts of the body: hands, face, neck and the eyes.

We distinguish between burns of the <u>first, second and third degree.</u> The degree of the burn depends on the light pulse, that is to say on the distance of the casualties from the site of the explosion, on its type, on the duration of the effect of the radiation, the position of the person with respect
1)
  "The effects of atomic weapons" , New York - London, 1950.

-154-

to the explosion, and the quality of his or her clothing.

First degree burns are caused by light pulses of approximately 2 - 4 cal/cm^2. (The lower limits relate to low-caliber bombs and the upper limits to large caliber ones).

Burns of this degree are accompanied by reddening of the skin AND some painfulness. If the hands, face and neck receive burns of this kind, the victims can carry on working to some extent, and can take part in further fighting. First degree burns heal up comparatively rapidly.

Second degree burns are characterized by blisters and require special treatment for a longer period. These burns are caused by light pulses 4 - 10 cal/cm^2.

As a rule, the second degree burn has a disabling effect on the sufferer. It is therefore considered that everyone who has been subjected to the effect of luminous radiation from a nuclear explosion at a distance at which the light pulse is strong enough to cause second degree burns is a potential CASUALLY. Obviously, some of the victims will not be disabled, since many will be protected to some extent from the luminous radiation.

Third degree burns are accompanied by the formation of sores, necrosis of the skin and subcutaneous tissues. These burns will be caused by light pulses 10 - 15 cal/cm^2. When the pulse is greater than 15 cal/cm^2 there is charring of the uncovered parts of the body. Third degree burns require prolonged treatment.

The division of burns into three groups is to some extent arbitrary, since there is no possibility of drawing a sharp dividing line between first and second degree burns and between second and third degree burns. Hence, at first sight it may seem difficult to determine between a severe second degree burn and a slight third degree one. The ensuing pathology of the injury, however, usually makes the distinction possible.

The degree of a burn is not the only factor to take into account when determining its effect on a human being. The size of the effected area of the skin is also of great importance. For example, a first degree burn all over the

-155-

body may be more serious than a third degree burn in any one point. The greater the burnt area, the greater the effect of the burn on the whole organism. Furthermore, there are critical areas, for example, the hands, which when burnt, usually disable the victim.

Fig. 51 enables us to determine the distances at which we can expect a degree of injury for different states of the atmosphere.

To do this, we draw straight lines in Fig. 51 parallel to the horizontal axis at distances equal to the pulse required to inflict a particular degree of injury. Having done this (for an atomic bomb with a TNT equivalent of 20,000 tons), we find that first degree burns can be expected in clear weather at 4000 - 5000 m, secondary degree burns up to 2500 m, and third degree burns up to 1500 m from the epicenter of the explosion. When the atmosphere is such that the attenuation factor is $k = 0.2$ (1/km), first degree burns are possible at distances up to 2700 m, and at $k = 2$ (1/km) up to 1200 m.

During the atomic explosions over Hiroshima and Nagasaki (TNT equivalent of these bombs was 20,000 tons), human skin was found to be charred over a radius of approximately 1200 m from the epicenter of the explosion. The heat of the explosion was felt at distances greater than 9000 m. It has been established that slight pain is experienced when a light pulse of 0.3 cal/cm^2 acts on the human body for one second. On the basis of the curves FOR pulse VERSUS DISTANCE for different states of the atmosphere and bomb caliber, we can always evaluate the radius of destruction by the light radiation from these bombs. The rough radii over which human beings are injured by luminous radiation, DEPENDING ON the size of the bombs (at a visibility of 25 km) are shown in Table 7 (here the time over which the radiation acted and the caliber of the bomb were taken into account).

Although uncovered parts of the body are mainly affected by the luminous radiation, in Hiroshima and Nagasaki cases were recorded in which skin protected by one or more layers of clothing received burns. These cases usually occurred on parts of the body where the clothing fitted tightly - elbows, shoulders and waist.

The parts of the body (back) where the clothing was looser were uninjured.

Table 7

Radii of injuries caused to human beings by luminous radiation (in kilometers) as function of the caliber of nuclear charges (for a visibility of 25 km)

Nature of injury	TNT equivalents				
	1000 t	20,000 t	1 million t	5 million t	10 million t
Third degree burn...	0,6	2,4	12,8	24,0	32,2
Second degree burn...	0,8	2,9	14,4	28,8	43,3
First degree burn...	1,1	4,2	22,4	36,4	51,3

Persons dressed in dark clothing received severer burns than those dressed in white or lighter-colored clothing. People wearing multicolored clothing received severer burns on those parts of the body lying underneath the dark colored patterns. One case occurred in which a woman dressed in a colored dress was only burnt at places lying directly beneath the dark pattern of the fabric (Fig. 58).

The degree to which the protected areas of the body are burnt depends to a large extent to the thickness and coarseness of the clothing. For example, there were cases in which people dressed in khaki uniforms did not suffer burns on their bodies although they were only 1500 m from the point of explosion (at this distance third degree burns were suffered on uncovered parts of the body).

Effect of light radiation on a person's eyes during a nuclear explosion is slight. Even those who were looking towards the explosion only suffered temporary loss of vision. This is due to the fact that the blinking reflex was an effective defense. Blinking takes less than 0.1 sec, that is many times less than the time taken by the luminous radiation. The numerous cases of burnt eyelids (but not eyes) in Hiroshima and Nagasaki show that during a bright explosion the blinking reflex is of great importance from the viewpoint of protecting the eyes from luminous radiation.

Of much greater danger to the sight is a nuclear explosion at a great

Fig. 58. Burns received as a result of the effect of luminous radiation. The skin is only burnt in places covered by the dark design on the fabric.

height, although it may be a long way away. This is because the radiation occurs very rapidly during such an explosion and the eye does not have time to close.

One should never try to look at the fireball in order to protect the eyes from luminous radiation during an explosion. The distinctive feature of luminous radiation burns is that they are strictly limited to the unprotected parts of the body turned towards the center of the explosion (source of light radiation). Such burns have been called "profile burns". Generally speaking, no burns were observed on covered or shaded areas of the body. This is simply due to the fact that luminous radiation is propagated in a straight line (in clear weather) and mainly affects the parts of the skin which are unprotected. The following examples of profile burns are known to have occurred in Hiroshima and Nagasaki.

A man was sitting by a window and writing; his hands were severly burned, but his uncovered face and neck were only slightly affected merely because the angle of incidence of the rays was such that they had no great effect on the trunk or face of the man (the angle of incidence was large).

Soldiers stripped to the waist at distances of 1800 m from the point of the explosion received burns on the side of their bodies facing the source of the luminous radiation. Fig. 59 shows a "profile burn", suffered by a soldier. His cap was sufficient protection and saved the top of his head from being burned.

Fig . 59. "Profile burn". The cap protected the top of the head from burns.

This means that a man in the shadow[1] cast by an object may totally avoid burns during the propagation of the light radiation.

It should be remembered that any opaque obstacle affording protection from the direct effect of light completely rules out the danger of burns in most cases. Ordinary uniforms also has a protective effect from luminous radiation during an atomic explosion.

Effect of luminous radiation on different materials. Luminous radiation from a nuclear explosion may cause more than burns on different parts of the body. It causes the ignition and charring of different combustible materials. Directly on the battlefield it may set fire to and char the wooden parts of armaments and equipment, may set fire to covers, the rubber rollers of tanks and trucks, or may scorch the paint off tanks and other armaments.

In dry weather the luminous radiation may cause fires in forestland or steppes. Fieldstores containing fuel, lubricants, munitions, and other items constitute the greatest danger. At naval bases mooring installations, small wooden craft and piers may be set on fire. Aboard ship canvas coverings, wooden floors, ropes and so on may be set on fire. Luminous radiation cannot cause any severe damage to the armament on ships. In certain cases, if its action is direct, it may char rubber shock absorbers, scorch or blacken paint, and so on.

On airfields the luminous radiation caused during a nuclear explosion may scorch the painted surface of aircraft, may set fire to coverings, blinds inside the aircraft, parachute containers, bits of cloth and so on.

In populated points the luminous radiation may cause fires by igniting wooden constructions, fences, barns, wrapping material stores and so on.

The approximate light pulses causing charring and stable combustion of certain materials as well as the distances over which these effects occur during an atomic explosion with a TNT equivalent of 20,000 tons in completely clear weather when the weakening of the luminous radiation in the atmosphere can be disregarded

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[1] This means the shadow cast by the luminous radiation from a nuclear explosion.

are shown in Table 8.

Such Loose / *Solid* combustibles as hay, straw and wood shavings present the greatest fire hazard.

Table 8.
Approximate light pulses causing charring and stable combustion

Material	Light pulse cal/cm²		Distance from epicenter of explosion, m
	charring	stable combust.	
Dry, unpainted boards................	4-5	40-50	1100-1300
Boards painted white.................	30-40	100-150	—
Dry hay, straw......................	2-3	4-6	3000-3500
Canvas..............................	30	40	1200
Light colored cotton cloth...........	4-6	10-15	2000-2500
Dark colored cotton cloth............	2-3	4-6	3000-3500
Khaki cloth.........................	4-6	8-10	2500-2700
Synthetic rubber....................	—	8-10	2500-2700
Bakelite............................	75	—	—

These pulses correspond to materials in the dry state. Light pulses several times greater (2 or 3 times or more according to the moisture content of the material) are required to cause the same amount of damage to moist materials. This means that in rainy weather the area of destruction due to the luminous radiation is less, first on account of the weakening of the radiation by the atmosphere, as well as the fact that greater pulses are required to cause the same amount of damage. During a ground-level (sea-level) nuclear explosion the distances over which there is the same amount of damage is less than in an aerial explosion since some of the luminous radiation is screened and absorbed by the dust raised by the shockwave.

It is pointed out in the foreign press that the outbreak of fires due to luminous radiation during an aerial nuclear explosion with a TNT equivalent of 20,000 tons is most probable over an area ranging from 0.8 to 3 km from the epicenter of the explosion. Some of the outside fires breaking out at distances more than 1 km from the epicenter are extinguished by the shockwave which reaches these distances when the effect of the luminous radiation is over. It is highly improbable that fires would break out on the outside of buildings at close

distances. The chief danger is the ignition of materials (window curtains, wall-
paper, rugs, clothing, upholstery and so on) inside buildings by the luminous
radiation entering through the window. Approximately 80 - 90% of the incident
light of the visible and close-lying infra-red regions of the spectrum (up to
3 microns) is transmitted by window glass. The light pulse required to set fire
to tulle drapes is 12 - 15 cal/cm^2. It should be remembered that practically any
FLIMSEY inflammable household object catches fire when subjected to a light pulse
of the order of 10 cal/cm^2.

Fires breaking out inside buildings are not extinguished by the shock-
wave. Thus, luminous radiation may cause a large number of small, rapidly spread-
ing centers of conflagration inside buildings the windows of which face the
explosion. The initial centers of the fire must be liquidated as soon as possible
to stop the fire spreading. Fire precautions put into effect beforehand are of
great importance.

As has been pointed out, fires may break out in populated points for
other reasons, for example, the destruction of stoves, boilers, short circuits in
the power supply, broken gas pipes, and what have you.

But the number of fires in the total area suffering thereby depends on
many things: the topography of the surrounding countryside, how close TOGETHER the
buildings are, their inflammability, the direction of the wind, the weather and
so on. It is therefore difficult to determine in advance the total area which
might suffer from the fire.

For example, during the atomic bombing of Hiroshima, which is situated
on flat terrain and had a large, densely built-up area, there were many con-
flagrations all at the same time. The smoke and hot air which rose up caused a
strong draft towards the center of the conflagration and made it much fiercer.
The wind velocity attained 60 km/hour, as a result of which 20 minutes after the
explosion there was a so-called "fire storm". It did not die down until six
hours later, and a certain contribution was made by the heavy rain which followed

the explosion. The narrow streets, which became impassable, prevented the population leaving the area wrecked by fire. That is why half the fatalities were due to the fire, and three quarters of the casualties received burns. Disorganization of the fire service made it impossible to extinguish the conflagrations.

As has already been pointed out, in Hiroshima 50% of the fire fighting equipment was destroyed through demolition of the fire stations, and 80% of the personnel were unable to take part in putting out the fires. The fires were able to spread more easily because both in Hiroshima and Nagasaki the water supply was almost completely destroyed. Serious damage was done to the main water pipes, causing leakage and a drop in pressure.

Practically all the wooden buildings within a radius of more than 3 km from the epicenter of the explosion were destroyed by this fire. Other buildings and installations over a wider area were also damaged by the fire.

Conversely, in Nagasaki, which is situated on hilly terrain there was no fire storm since the hills acted as an obstacle in the path of the fire, and acted in much the same way as the clearings which prevent fire spreading a forest. It is known that on the far side of the hills in Nagasaki houses only experienced slight damage, while in Hiroshima at the same distance from the point of the explosion (on flat terrain) they were totally demolished. The hills also shaded the direct rays of light from the fireball. A fire storm need not only occur during a nuclear explosion. Cases are known in which a large number of fires are caused by high explosives and incendiary bombs. For example, when Hamburg was bombed during World War II, 16,000 houses were set on fire at the same time and the temperature of the air in the region of the fire attained 800°. In the air-raid shelters the air rose in temperature and people sheltering in them DIED OF heat stroke. Those who tried to escape through the blocks of flaming buildings were burned alive. Even before this a large number of people were poisoned by the carbon monoxide contained in the smoke from the fires (if the air contains 0.5% carbon monoxide, human beings die within 10 minutes). The storm

-162-

tor e doors off the airraid shelters and allowed the carbon monoxide to get inside. A hundred thousand people in all were killed in Hamburg. These figures show that great caution should be shown in deploying troops in large cities during wartime.

A detailed study of the major conflagrations have shown that, all other things being equal, the most important criterion for the probability of the fire spreading is the distance between buildings. Obviously, the less built up the area, the less likely it is that the fire will jump from one building to another. Furthermore, the greater the distance between buildings, the easier it is to extinguish the fire.

It is also well known that the accumulation of combustible material in constructions, especially wooden ones, constitutes a real fire hazard.

The great importance of fireproof finishing has been established. Foreign literature[1] quotes a case occurring during nuclear tests. Two identical houses (each with a window facing the explosion) were subjected to luminous radiation of 17 cal/cm^2. One house contained artificial silk upholstery, cotton rugs and curtains. During the explosion this house was instantly set on fire and burnt to the ground. In the other house the upholstery was made of vinyl plastic, and the rugs and curtains were made of wool. Although fire broke out inside the house at several places, it was put out by a team of firemen arriving an hour after the explosion.

Protection against luminous radiation from a nuclear explosion. During a nuclear explosion over open terrain humans are subjected to a combination of destructive factors. Anti-atomic defense should therefore include measures for protection against all these factors.

However, when considering A series of measures DESIGNED/ TO AFFORD simultaneous protection against all the harmful factors, we have to know the specific features of each factor separately.

Fig. 60 shows a diagram of a cross-cut through a trench. It is clear

from the drawing that the steepness of the walls of the walls of the trench affords protection from the direct action of luminous radiation.

But can it be said that by ensuring protection from the direct rays of light we totally eliminate the damaging effect of the luminous radiation? No, we can not. Indeed, the rays striking the walls of the trench are partially reflected (shown by the broken lines and arrows in Fig. 60). This reflected radiation may injure people on the bottom of the trench (burns). When the luminous radiation strikes the walls of the trench, the extent of the injuries caused to people inside depends on the reflectivity of the wall and the distribution of the reflected light through space with respect to the point of incidence of the rays.
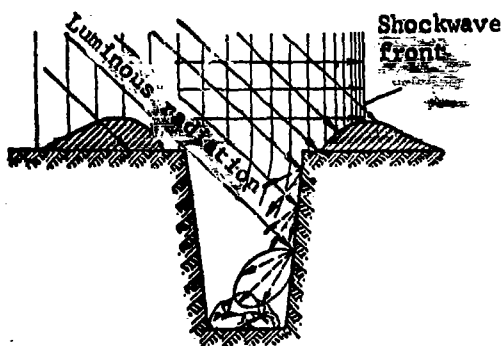
Fig. 60. A trench weakens the destructive effect of luminous radiation from an atomic explosion

Thus, it cannot be said that protection from the direct rays in an open trench can always eliminate injury due to the luminous radiation from an atomic (hydrogen) explosion. This is even less the case when there are clouds, as already mentioned above. At the moment of an atomic explosion people in open trenches should lie face down to reduce the injurious effect of the luminous radiation reflected from the walls and clouds, as shown in Fig. 60.

Naturally, in many cases the reflection of the radiation from the wall may not actually be of danger to the persons inside, but this fact must be taken into account when organizing anti-atomic defense measures.

-164-

How can we improve the protection afforded by fortifications? It can be done, partially, by building covered slit trenches or covering certain parts of other trenches.

A covered slit trench or the covered part of a larger trench not only totally eliminates the effect of the luminous radiation, but gives more reliable protection from penetrating radiation, shockwave and to some extent radioactive dust.

Protection from luminous radiation is much simpler than from the other destructive factors. As already pointed out, luminous radiation spreads mainly in a straight line in clear weather, hence any opaque obstacle or any body casting a shadow can act as protection.

By sheltering in trenches, pits, ditches, shell holes, behind mounds, embankments, large-size military equipment, trees and so forth, we can greatly reduce luminous radiation burns or avoid them entirely. The cabins of ships provide good protection from luminous radiation.

It should be kept in mind that about 85% of the luminous energy is radiated (in approximately one second after the explosion. Hence, having seen the flash, people should take shelter immediately, without the slightest delay. If there is no shelter within reach, people should certainly not run and look for it. They should lie flat on the ground, face down, with their legs towards the explosion. The hands should be hidden underneath, the eyes closed to avoid a possible temporary loss of vision. If these rules are observed, the harmful effect of the shockwave will be reduced to a considerable extent and the uncovered parts of the body (face and hands) will be saved from the luminous radiation.

If equipment and clothing catch fire, the person involved should never run since this only helps the combustion. The flames should be extinguished by pressing the burning part against the ground. When helping a comrade we should throw a ground sheet or great coat on top of him and press it firmly against his body, as shown in Fig. 61. Areas subjected to burns should be immediately bandaged

usi ng the soldier's own dressing pack. If the clothing is stuck to the burnt area, it should not be pulled away, and the dressing should be applied over the clothing. In no case should the blisters formed on the skin be broken.

Burning vegetation, the coverings on trench walls and various other pieces of equipment should be extinsuished with sand, earth, fire extinguishers or wet brooms and rags.

Fire prevention is made considerably easier if certain precautions are observed beforehand. These are aimed at reducing the possibility of an outbreak of fire, creating conditions which reduce the spread of fires and easing the actual fire fighting.

Fig. 61. Burning clothing should be extinguished with a ground sheet or great-coat pressed close to the body.

Let us look at some of these precautions. All open, wooden areas of defense installations for protection from luminous radiation must be smeared with clay (earth) or lime, and at intervals of 40 or 50 m along the walls of trenches there should be sections 1 to 2 m long. Dead wood, pine cones and dry grass are removed from the area around defense installations in forest land, and light wooden constructions and defenses in populated points are pulled down.

Aboard ships, easily inflammable equipment (covers, TARPAULIN DECKS , etc.), should be periodi cally hosed down since a considerably greater light pulse (2 or 3 times greater, according to how wet the material is) is requued to ignite or char wet materials than dry ones.

To stop the spread of forest fires clearings should be made 5 - 10 m in width, and they should be cleared free of dead wood and dry grass; in steppeland strips should be plowed, etc. Troops should be equipped with fire fighting equipment.

Fire precautions are particularly important in populated points. All inflammable materials MUST BE removed from attics and staircases. Open, wooden structures, including inflammable attics, should be impregnated or painted with special fireproof materials or coated with liquid clay to improve their fire-resistance. If the attic roofs contain inflammable insulation (peat, shavings and so on), they should be replaced by non-inflammable ones, or else strewn with sand, earth, or clay 10 - 15 cm thick.

Some wooden structures (barns, houses, fences, and so on), as already mentioned, are pulled down, while other inflammable materials (wrappings, wooden storehouses, etc.), are taken away or covered with fireproof canvas.

To prevent the luminous radiation entering buildings through windows, the window panes should be whitewashed.

Window glass transmits about 90% of the incident luminous energy within the visible and close-lying infra-red regions of the spectrum (up to 3 microns). At the same time glass practically totally absorbs ultra-violet light and the longwave region of the infra-red spectrum (more than 3 microns). The absorption capacity of window glass with respect to the visible and infra-red rays can be increased by whitewashing it. Whitewashed glass keeps out about 80% of the luminous radiation. The whitewash should be made from the following recipe[1]: unslaked lime, grease and water in the proportion 10:1:30 (two coats are applied to the outside of the window).

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[1] D. I. Lawson. Atomic bombs and conflagrations. Translation from English. Foreign Literature Press, 1955.

To prevent flying glass broken by the shockwave, window panes should be pasted over with white cloth, or paper.

Clothing, books and other inflammable objects should be put away in tightly sealed cupboards or boxes. All extra stocks of combustible materials must be taken away from rooms. In apartments paraffin should only be kept in small quantities in iron, tightly sealed containers. Particular attention should be given to instructing people in fire precautions and in the use of the simpler fire fighting methods.

In populated points arrangements should be provided for extinguishing fires in case the main water supply is put out of action.

A nuclear explosion may be followed by a large number of small fires. The teams of firemen cannot be expected to cope with fires encompassing a region of several kilometers. They will have to be assisted. Minor fires have to be discovered and liquidated in time, before they can spread. One of the lessons of the atomic bombing of Hiroshima and Nagasaki should be remembered *above all*. The water supply was cut off on account of the destruction of houses and the main water pipes.

Hence certain industrial plants and regions of cities should be provided with tanks or reservoirs with sufficient capacity (ponds and lakes are important in this respect) to hold the water required for firefighting purposes.

Observations of these rules will reduce the number of victims and potential fires to a tremendous extent during an atomic explosion.

The matter set forth in this section should not, of course, be regarded as having exhausted the problem of defense against luminous radiation. We only give the basic information here. Nevertheless, a firm knowledge of the harmful factors in a nuclear explosion and their effects will help people to decide sensibly what methods of protection to apply in the given situation, and to reduce the losses and damage caused.

CHAPTER IV

GENERAL INFORMATION ON PROPERTIES OF NUCLEAR RADIATION

1. Radioactivity

Nature of radiation. A characteristic feature of a nuclear explosion is the penetrating radiation emitted by the atomic nuclei. This radiation is accordingly termed nuclear radiation. Before studying the nuclear radiation from nuclear explosions we should familiarize ourselves with the principle properties of this effect in the general form. In nature nuclear radiation may be electro-magnetic or it may be a stream of rapidly moving elementary particles (corpuscular radiation). The energy of the quanta of visible light (light photons) only constitutes a few electron volts, while the elementary particles escaping from the atomic nuclei may possess energy equal to several billion electron volts. Nuclear radiation is invisible and cannot be directly sensed by human beings. A general characteristic of all nuclear radiation is its ability to form elect-rically charged particles - ions - in the media through which it passes. Hence nuclear radiation is conventionally classed as ionizing radiation, which also includes cosmic, x-ray and ultra-violet radiation.

As we shall see later on, the ionizing effect of this radiation makes it biologically harmful to living organisms.

The electromagnetic radiation emitted by atomic nuclei is convention-ally known as gamma radiation. In principle gamma rays are no different from short-wave x-rays, which are usually taken to mean radiation emitted by the electron shell and the fast electrons when decelerated. They exist in the form of separate portions - quanta - which possess definite energy. The relationship between wavelengths of electromagnetic radiation and the energy of the quantum is determined by a simple equation $E_\gamma = (1.234 \cdot 10^{-4})/\lambda$, where E_γ is the quantum energy in the electron volts and   is the wavelength in centimeters.

The greater the quantum energy, the shorter the wavelength of the radiation and vice versa.

It is conventional to distinguish between hard gamma radiation ($E_\gamma > 1$ Mev) and soft gamma radiation ($E_\gamma < 1$ Mev) according to the energy of the quanta.

The source of gamma radiation is "energy-excited" atomic nuclei, that is to say the atomic nuclei possessing surplus energy, compared with their normal state. It has been established by modern nuclear physics that a nucleus cannot remain for a long time in the excited state, and releases its excess energy within approximately 10^{-13} sec, most often by emission in the form of 1 or more quanta.

Excited nuclei may be engendered by radioactive decay or else by the interaction of nuclei and elementary particles, or other nuclei.

Corpuscular radiation constitutes streams of fast-moving elementary particles : neutrons, protons β and α particles.

The neutron is an elementary particle without an electric charge; its mass is close to that of the nucleus of the hydrogen atom. Let us recall once again that the neutron is contained in all atomic nuclei with the exception of light hydrogen. In the free state the neutron survives a short time only, since it is rapidly captured by atomic nuclei or turns into a proton by losing an electron.

On the basis of their kinetic energy we distinguish between fast neutrons ($E > 1$ Mev) intermediate neutrons (0.01 Mev $< \underline{E} < 1$ Mev) and slow neutrons ($\underline{E} < 0.01$ Mev).

The velocity of motion of a neutron can be determined from the following equation if we know the energy

$$v = 1.38 \cdot 10^4 \sqrt{E} ,$$

where $\underline{v}$ is the velocity in m/sec;

$\underline{E}$ is the energy in ev.

It should not be thought that a slow neutrons moves at a slow pace. Indeed, taking the energy of a slow neutron to be 1 ev, we find that $\underline{v} = 1.38 \cdot 10^4 \sqrt{1} = 1.38 \cdot 10^4$ m/sec, that is to say a slow neutron moves at a rate considerably

-170-

exceeding the velocity of an artillery shell or a modern jet aircraft.

Neutrons emitted by atomic nuclei may possess energy considerably exceeding 1 Mev.

Beta radiation is a stream of β -particles, that is to say electrons or positrons (positively charged electrons).

Radioactive isotopes are SOURCE of beta radiation. The energy of the beta particles emitted by radioactive nuclei may attain several megaelectron volts. At energies of this kind, the electron (positron) moves at a velocity close to the speed of light in a vacuum (300,000 km/sec).

The proton is the nucleus of the atom of light hydrogen. It constitutes a positively charged particle making up the atomic nuclei of all elements. As already pointed out, the absolute value of the charge of a proton is equal to that of one electron. Protons present in the free state rapidly turn into hydrogen atoms by annexation of the free electrons. Protons are emitted by atomic nuclei as a result of various nuclear reactions, in particular by the absorption of neutrons by the nuclei of certain atoms.

Alpha radiation is a stream of fast moving helium nuclei, consisting of two neutrons and two protons. Thus, an α -particle is a positively charged particle, and its charge is equal to two electron charges. The energy of α -particles emitted by atomic nuclei may attain 10 Mev or more. At this energy alpha particles have a velocity of about 20,000 km/sec.

Radioactive decay of atoms. Radioactivity means the ability of certain substances to emit nuclear radiation without outside stimulus.

It has been established by extensive scientific research that radio-activity is associated with the arbitrary transformation (decay) of nuclei of the atoms of one element into another element. The nuclear radiation accompanying the decay is said to be radioactive.

At the present time we know of more than 700 radioactive isotopes, only a few of which exist in nature, while the remainder are obtained artificially.

-171-

In a number of countries radioactive isotopes of absolutely all the known chemical elements have been obtained in the laboratory. Artificial radio-active isotopes are obtained in the laboratory by bombarding atomic nuclei with neutrons, protons, deutrons (heavy hydrogen nuclei) and helium nuclei. To boost the protons, helium nuclei and other charge particles, use is made of special equipment (cyclotrons, betatrons and so on). Radioactive isotopes can be produced in very large quantities in nuclear reactors where they occur during the fission of heavy nuclei (uranium, titanium) or by irradiation stable isotopes with a neutron stream. A nuclear explosion is a powerful source of artificial radioactive isotopes, as will be discussed in detail in Chapter VI.

There are three basic types of radioactive decay: <u>alpha-decay,beta-decay</u> <u>and electron capture.</u>

During α-decay, the nucleus emits an alpha particle. Since the alpha particle possesses two units of positive charge and a mass number equal to 4, after it has escaped from the nucleus the atomic number of the newly formed nucleus is two units less than the original one, while the mass number is 4 units smaller.

For instance, plutonium 239 atoms are converted into uranium 235 atoms, the nuclei of which have a charge two units smaller and a mass number four units smaller than the plutonium nucleus. This decay can be written down in the abbreviated form as the equation

$$_{94}Pu^{239} \rightarrow {}_{92}U^{235} + {}_{2}He^{4}.$$

Alpha decay is mainly found in natural radioactive elements at the end of the periodic table (radium, uranium, thorium and so on).

As a rule, alpha particles emitted during the decay of the given isotope possess definite energy.

During beta decay the nucleus emits an electron (β-decay) or a positron (α-decay).

When an electron is emitted, the original atom turns into a second atom with a charge one unit greater, since the loss of one negative charge is equal to

-172-

the acquisition of one positive charge. The mass of the electron is small
(0.0005 aum), hence the atomic weight of the newly formed nucleus is virtually
unchanged.

For example: $_{11}Na^{24} \rightarrow {}_{12}Mg^{24} + \beta^-$.

Electronic beta decay is the commonest form of radioactive decay;
beta-active isotopes constitute about 46% of the total number of radioactive
isotopes.

The statement that an electron escapes from a nucleus may cause
objection from readers since there are no electrons in the nucleus. Nevertheless,
this statement is not erroneous. The point is that neutrons and protons which
make up the nucleus may change into each other under certain conditions, and
an electron or positron is engendered during the process. The escape of an
electron is a signal that one of the neutrons has turned into a proton.

When a positron is emitted, the original atom turns into another atom
with a charge with one unit less, since one of the protons has become a neutron
as a result of the positron beta decay.

For example: $_{14}Si^{27} \rightarrow {}_{13}Ae^{27} + \beta^+$.

On account of the fact that during this decay the proton is turned into
a neutron, it is only found in isotopes with a deficiency of neutrons, that is
in the lightest isotopes of chemical elements. Positron decay is considerably
less common than electron decay, and is only found in about 11% of all radio-
active isotopes, while those with a large atomic number Z hardly exhibit any at
all.

In different atoms of the same radioactive substance the initial
energies of beta particles may range from 0 to a certain maximum E_β, which is
characteristic of each radioactive isotope. For example, for strontium 89 the
maximum beta energy particle is not greater than 1.5 Mev, in cobalt 60 it is
0.3 Mev, and so on. A maximum beta particle energy emitted by most radioactive
products during an atomic explosion is not greater than 3 Mev. On account of the

difference in energy of individual beta particles, their initial velocity may range from zero to velocities close to the speed of light. This distribution is conventionally called the energy spectrum of the β-particles. For a long time it was not clear why the nuclei of the same isotope emitted beta particles with different energy, or what happened to the energy when the beta particle escaped from a nucleus with energy less than $\underline{E}_\beta$. The correct explanation of this feature of beta decay was found after it was assumed that a second particle, called the neutrino, was emitted from the nucleus at the same time as the beta particle. The total energy of the neutrino and the beta particle are exactly equal to $\underline{E}_\beta$. The neutrino does not have an electrical charge and its mass is much smaller than that of the electron.

Electron capture is radioactive transformation which, just like β^{+-}-decay, was discovered during the study of artificial radioactivity. In electron capture the radioactive nucleus captures one of the electrons from the K-shell (or more rarely the L-shell), on account of which one of the protons turns into a neutron, and the charge of the nucleus is reduced one unit. More than 25% of all radioactive isotopes decay through electron capture and, just as β^{+}-decay, it is only found in isotopes with a neutron deficiency.

In many radioactive isotopes beta- and alpha-decay and electron capture are accompanied by the emission of gamma radiation. Gamma quanta are radiated by atomic nuclei whenever the newly formed nucleus is energy-excited after decay; when changing to a state with less energy the nucleus emits its surplus energy in the form of one or more quanta. For example, the beta decay of sodium 24 is accompanied by the emission of two gamma quanta. It should be pointed out that the γ-quantum does not have an electric charge, hence when emitted the charge of the nucleus remains unchanged and there is therefore no radioactive decay of the atom.

Law of radioactive decay. Unit of activity. Radioactive decay does not take place all at once in atoms, but stage by stage. Only a certain number

of radioactive atoms decay each second. But each radioactive atom undergoes transformation sooner or later. The law governing the reduction in the radioactive atoms is simple: half any quantity of atoms of a given radioactive substance decays within a certain time. Hence to describe the decay of a radioactive element we usually use a quantity conventionally termed the half-life. The half-life T is the interval of time within which half the atoms which existed at the beginning of this interval have decayed.

The half-life of different radioactive isotopes ranges over wide limits from fractions of a second to many billions of years.

For example, the half-life of radioactive strontium 89 is 54 days. If we take a certain amount of radioactive strontium, after a period of 54 days half the radioactive atoms are left. After a period equal to two half-lifes ($2T = 108$ days) a quarter of them are left; after 3 half-lifes ($3T = 162$ days), an eighth is left, and so on.

The half-life of plutonium 239 is high and equal to 24,000 years. This means that it is not until 24,000 years later that half the atoms of the given amount of plutonium decay. Uranium 235 has the greatest half-life - 710 million years. By knowing the half-life of a radioactive isotope, it is not difficult to determine the number of non-decay radioactive atoms at any moment of time

$$N = \frac{N_0}{2^{\frac{t}{T}}},$$

where N_0 is the original number of radioactive atoms;

N is the number of non-decayed atoms;

t is the time which has elapsed from the moment the number of atoms was N_0.

The rate of radioactive decay does not depend upon physical or chemical conditions, that is to say that there are no methods by which we can step up or slow down radioactive decay.

The number of atoms decaying in one second is called the activity of

the substance. The more atoms there are in the radioactive matter and the shorter their half-life, the greater the activity of their substance. If the half-life T is expressed in seconds and N denotes the number of radioactive atoms, the activity of a substance $\underline{Q}$ is equal to $Q = 0.693 \cdot \dfrac{N}{T}$.

The amount of radioactive matter is usually assessed on the basis of its activity, and not by its weight in grams. This is due to the fact that the operation of weighing radioactive matter, even under laboratory conditions, is extremely difficult since its mass is usually extremely small and, furthermore, radioactive isotopes are usually mixed with other substances, including nonradioactive matter.

Unit of activity and therefore the amount of radioactive matter is usually termed the curie.

The curie is the amount of radioactive matter in which 37 billion atoms decay every second.

Each atomic decay is accompanied by the emission of an alpha or beta particle, hence the activity of 1 curie corresponds to the emission by the radioactive substance of 37 billion beta or alpha particles per second.

The number of gamma quanta per decay may differ. For example, in the isotope cobalt 60 (Co^{60}) each atomic decay is accompanied by the emission of two gamma quanta, the isotope manganese 54 (Mn^{54}) the decay of each atom is accompanied by the emission of one gamma quantum, and so on. Thus, to determine the number of gamma quanta radiated by a gamma-active substance, apart from the activity expressed in curies, we have to know the number of gamma quanta per atomic decay.

The longer the half life, and the greater the mass number of the radioactive isotope, the greater the amount of the substance per curie in terms of weight. The amount in weight of radioactive atoms with an activity of 1 curie can be determined from the equation

$$M = 0{,}89 \cdot 10^{-13} A \cdot Tr,$$

where $\underline{A}$ is the mass number;

$\underline{T}$ is the half-life in seconds.

A curie of radium weighs one gram and occupies a volume the size of a small pea. One curie of cobalt 60 with a half life of $\underline{T} = 5$ years is a bead of metal weighing about one thousandth of a gram.

One curie of radioactive substance, the half-life of which is reckoned in hours or minutes, contains a particularly small amount in weight. One curie of sodium 24 weighs about 1 ten millionth of a gram. But almost always in practice the radioactive substance is mixed with non-radioactive substances, and the amount of this mixture in weight corresponding to an activity of one curie may be considerably greater than when calculated from the given equation.

2. Interaction between nuclear radiation and matter

Interaction between fast-moving charged particles and matter. Alpha-beta-particles and protons are electrically charged particles. Hence when they pass through matter, they interact electrically with the electrons and nuclei on the atoms.

The interaction between fast-moving charged particles and matter may be accompanied by the following effects:

1) ionization and excitation of the atoms;

2) loss of energy on bremsstrahlung.

The process of ionization by a charged particle is as follows. When the charged particle passes a long way from the atom, it does not react with it, since the atom as a whole is electrically neutral. But if the particle enters the atom shell or passes near it, forces of electric interaction occur between the particle and the atom's electron. These forces throw one or more electrons out of the atom. Thus, when a charged particle encounters an atom, it ionizes it and loses some of its energy. The ionizing capacity of charged particles is conventionally described as the specific ionization, which is the number of pairs of ions created by a particle over distance 1 cm. The ionizing power of particles increases with their electric charge and the reduction in velocity of

-177-

the particle.

Bremsstrahlung is the result of interaction between a charged particle and electric field of the atomic nucleus. When this particle passes close to the nucleus, it is brought to a halt by the electric charges. We know from textbooks on physics that every deceleration of the motion of an electric charge must be accompanied by the emission of electromagnetic energy. The particle usually emits this energy in the form of an x-ray quantum.

Investigation of this type of interaction shows that the radiated energy proportional to the square of the atomic number of the substances in which the charge particle moves, and inversely proportional to the square of the mass of the charged particles. This means that the relatively heavy $\propto$ -particles and protons spend very little energy on the bremsstrahlung, compared with β - particles. For example, a proton whose mass is approximately 1836 times larger than that of the electron loses $(1836)^2 \cong 34 \cdot 10^5$ times less energy than a β -particle. Thus, for $\propto$ -particles and protons the chief result of the interaction with matter is the ionization and excitation of the atoms. In the case of fast β -particles passing through such heavy elements as lead, the energy losses on bremsstrahlung may be commensurate with the energy losses of ionization.

As the alpha particles and protons move through the substance, their velocity is reduced on account of ionization and excitation losses, and at a certaindistance they eventually become equal to the velocity of motion of atoms and molecules of surrounding matter. This distance is called the pathlength of the particle in the substance. Decelerated alpha particles are turned into helium atoms (hydrogen atoms) by combining with electrons.

The specific ionization of $\propto$ -particles is enormous. In air an $\propto$ - particle creates an average of about 30,000 pairs of ions over distances of 1 cm. The specific ionization differs at different parts of the pathlength of $\propto$ -particles, just as it does for other charged particles. At the beginning of the path it stays constant, but at the end of the path it is more than doubled,

-178-

and in the case of α-particles amounts to 65,000 pairs of ions.

The great ionizing power of α-particles means that the path length is usually not greater than 10 cm, even in air. For example, the pathlength of α-particles emitted by plutonium and uranium (with energy of about 5 Mev) in air is not greater than 4 cm, and is not greater than 0.0045 cm (45 microns) in human tissue. Beta particles are completely absorbed by clothing; even a sheet of paper is an insuperable barrier for them. The proton is also a strongly ionized particle. In air a proton creates an average of about 10,000 pairs of ions over a distance of 1 cm. The penetrating power of protons emitted by atomic nuclei is also very small. Their pathlength is approximately 4 times greater than for α-particles.

As the β-particles penetrate into the substance, they also gradually lose their energy and eventually become equal in energy to the average energy of atoms and molecules of the medium at a certain distance, INSIDE. The pathlength of beta particles in the given substance depends on their energy. The greater the initial energy of the particle, the greater its path in the given substance. However the energy of beta particles emitted by nuclei of the same isotope is differnt, hence the weakening of a beam of beta-particles does not occur imediately, but stage by stage. The distance over which beta particles are totally absorbed by a layer of substance is termed the maximum path. At the given energy the maximum path is inversely proportional to the density of the material and depends on the atomic number of the elements making up the material to a comparatively small extent.

Table 9 shows the maximum paths of β-particles for aluminum, water (human tissue) and air.

It follows from the table that although the penetrating power of beta particles is many times greater than alpha particles, it is also small. Beta particles are greatly attenuated by clothing and are virtually entirely absorbed by windowpanes or windshields, and any other metal screens several millimeters

Table 9

Maximum paths of β-particles as function of their energy

Maximum energy of β_m particles Mev	Al, mm	Water or human tissue	Air, mm
0,5	0,593	1,87	119
1	1,52	4,80	306
2	3,51	11,1	710
3	5,5	17,4	1100
5	9,42	29,8	1900

thick.

Beta particles possess far less ionizing power than alpha particles. This is due to the fact that beta particles which have a negligibly small mass compared with alpha particles exhibit much greater velocities for the same energy. Hence beta particles hurtle through the atom much too rapidly and on account of the small interaction time often do not manage to extract an electron, which MIGHT be extracted BY AN ALPHA PARTICLE MOVING RELATIVELY MORE SLOWLY. Furthermore, the electric charge of the alpha particle is double that of the beta particle, as a result of which at the same distance the force of electric interaction of the detached electron and alpha particle is double that of the beta particle.

The total number of pairs of ions formed by a charged particle is equal to its initial energy divided by the ionization work. The ionization work is the mean energy spent on the formation of one pair of ions. Its magnitude depends on the nature of the ionized medium, the type of radiation and certain other factors. In air the mean ionization work can be taken for all nuclear radiation as approximately 32.5 ev.

If the β-particle has an initial energy of 1 Mev, the total number of pairs of ions formed by it in air will therefore be $(1 \cdot 10^6)/32.5 \approx 30,000$. By dividing the total number of pairs of ions by the pathlength of the beta particle in air we get the mean specific ionization. For an energy $E_\beta = 1$ Mev, according to the data in Table 9, the maximum path is 3 m; hence, the mean specific ionization is ~ 100 (pairs of ions)/cm, whereas for alpha particles it

is several tens of thousands of pairs of ions over the same distance.

Interaction between gamma radiation and matter. The fact that gamma quanta have no electric charge means that the nature of their interaction with the medium through which they are propagated is quite different from the alpha and beta particles, which have electric charges. We know of three basic processes between gamma quanta and the atoms of the medium: photoelectric absorption, the Compton effect and formation of pairs.

During photoelectric absorption (Fig. 62a) there is interaction between the gamma quanta and the electrons in the atoms resulting in the gamma quantum being totally absorbed by the atom. Some of the energy of the gamma quantum goes into overcoming the bond energy of the electron in the atom, while the remainder is used to impart velocity to the electron. The detached electrons move preponderately in directions perpendicular to the propagation of the gamma rays.

In the Compton effect (Fig. 62b) the gamma quantum interacts with the electron of the atom, changing direction of motion and transmitting some of its energy to the electrons. This energy, just as the absorbed energy in photoelectric absorption, is spent on detaching the electron from the atom and on imparting velocity to it.

The scattered (remaining) γ-quantum has less energy, hence it has a longer wavelength. It moves at a random angle to the initial direction, but the angle decreases, on the average, as the energy of the primary γ-quantum increases. The Compton effect makes the γ-quanta a scattered radiation, which as distinct from a direct beam of γ-quanta, does not exhibit any clear-cut directivity.

As a rule, the gamma quanta are scattered a number of times and the scatter ends up with photoelectric absorption.

Finally, when the energies are greater than 1.02 Mev, gamma quanta may be turned into pairs of particles - positrons-electrons (Fig. 62c) - through
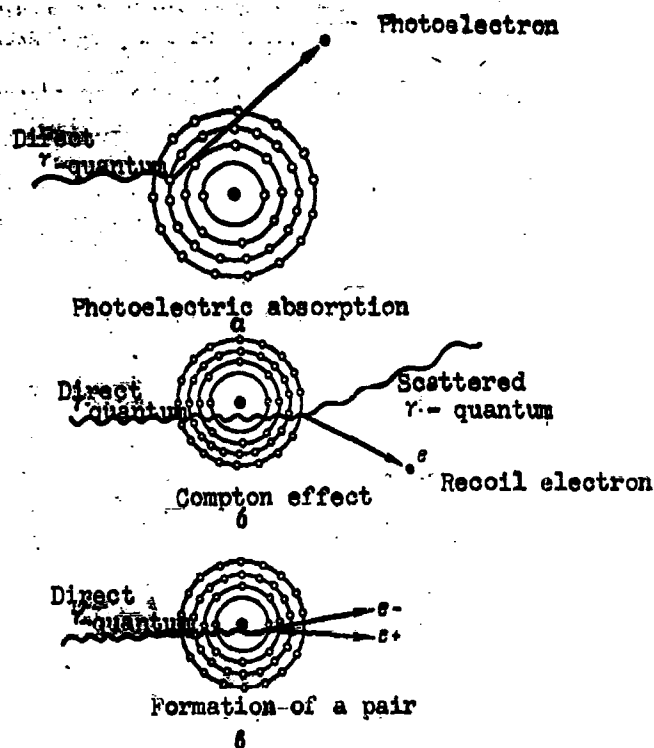
Fig. 62. Types of interaction between gamma quanta and matter.

interaction with the atomic nucleus. But this process only becomes predominant when the energies of the gamma quanta are very high and the substances have a large atomic number Z.

Photoelectric absorption is characteristic of low-energy gamma quanta (hundredths of a million electron volts), with the exception of substances with a high atomic number Z, where it may predominate and at considerable quantum energies (in lead with Z = 82 the process is predominant up to E_{γ} = 0.5 Mev).

In light substances (air, water, concrete, soil and so on), which are composed of elements with a low atomic number, the predominant process of interaction over a wide range of gamma quanta energies (from 0.05 to 10 Mev or more) is the Compton effect.

Ionization of the medium when gamma radiation passes through it is due mainly to the secondary electrons which occur as a result of the three processes of interaction which we have considered above. The ionizing power of γ-quanta is hundreds of times lower than in beta particles, and thousands of times lower than in alpha particles. The specific ionization of γ-quanta in air is several pairs of ions over a distance of 1 cm.

It was mentioned earlier that the Compton effect caused the scatter of γ-quanta. Hence after gamma rays have passed through a certain thickness of substance, the beam consists of a direct stream of γ-quanta which had been unaffected by their passage through the medium, and a scattered beam.
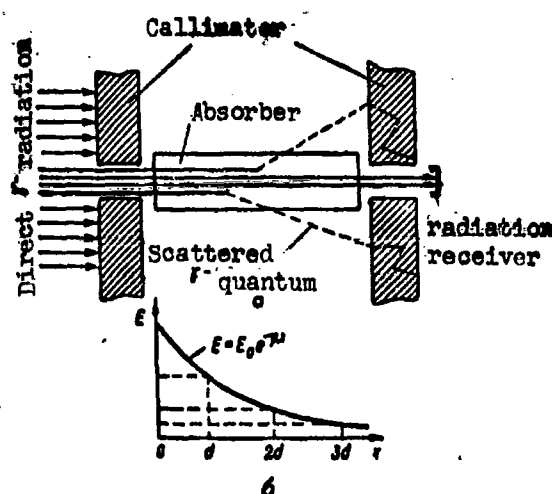
Fig. 63. Weakening of intensity of narrow parallel beam with gamma rays:
a) experimental plant for producing beams of gamma radiation with good geometry; b) law governing weakening of intensity of narrow parallel beam of gamma rays.

The intensity of a straight stream of gamma quanta can only be measured experimentally in cases in which all the scattered quanta leave the beam. If the beam is extremely narrow, even those gamma quanta scattered at small angles will leave it. Hence the laws governing the weakening of a direct stream of gamma quanta and a narrow beam are the same. Fig. 63a shows an experimental plant used

-183-

to create very narrow beams of parallel radiation, which are sometimes called beams with "good geometry". The apparatus consists of solid lead plates with narrow openings through which a beam of gamma radiation is transmitted. None of the gamma quanta deflected from the axis of the beam are able to act on the radiation receiver since they are absorbed by the solid lead plates in the first and second collimators.

Experimental data on the weakening of narrow, parallel beams show that the intensity of a direct stream of gamma quanta varies exponentially with the thickness of the layer of attenuating material (Fig. 63b)

$$E_x = E_0 e^{-\mu x},$$

where E_0 is the intensity of the radiation at the point where the rays enter the absorbing medium;

E_x is the intensity after they have passed through a thickness of x centimeters;

μ is the linear attenuation factor of the gamma radiation, and has the dimension 1/cm.

The factor μ describes the probability of interaction between a gamma quantum and atoms of the material over a distance of 1 cm. The numerical value of this factor is found to be a complex function of the gamma quantum energy, the atomic number and the atomic weight of the elements making up the protective thickness.

The reciprocal of the attenuation factor $\lambda = 1/\mu$ is called the mean path of the γ-quanta in substance and is numerically equal to the thickness when passing through which the intensity of a narrow parallel beam is reduced e times, that is to say, approximately by a factor of 2.7.

The weakening of the gamma radiation is due to the three types of interaction between the quanta and the medium, hence the factor μ is the sum of the three factors: photoelectric absorption μ_{ph}, the Compton scattering μ_c and the formation of pairs μ_p. Table 10 gives the factor μ as function of the

-184-

γ -quantum energy for different media.

A weakening on the intensity of gamma rays is quite often described by the magnitude of the layer of half-weakening, d, rather than by the factor μ. The half-weakening layer is the layer of material, during passage through which the intensity of the gamma rays is halved. There is a simple relationship between the factor μ and the half-weakening layer $d = (0.693)/\mu$. Just as the factor μ, the half-weakening layer is a complex function of the γ -quantum energy and the properties of the material. In media consisting of materials with close atomic numbers, the half-weakening is inversely proportional to the density of the material.

When the half-weakening layer is known, the multiplicity of the weakening of the radiation intensity after passage through the barrier x cm thick is equal to $E_0/E_x = 2^{\frac{x}{d}}$.

Table 10 gives the thicknesses of half-weakening layers d for a narrow parallel beam of gamma radiation as a function of the γ -quantum energy.

Analysis of the table shows that the penetrating power of gamma rays is immeasurably greater than beta, and particularly alpha rays. Gamma rays (energy of the quantum equal to Mev) are only weakened by a factor of 2 when they pass through 120 m of air, whereas alpha rays are totally absorbed by a layer of air several cm thick. A layer of aluminum 8 cm thick weakens a narrow, parallel beam of gamma rays (quantum energy 1 Mev) by only a factor of 4, though beta particles with the same energy are totally absorbed by a layer of aluminum 1.5 mm thick.

The intensity of a diverging beam of gamma rays is reduced both by weakening of the variation by the medium, and also by an increase in the distance from the source. Let us assume that a point[1] source radiating gamma rays in all directions uniformly emits N quanta per sec, each of which possesses the energy E_γ. Then, provided the medium does not weaken, the intensity of the radiation at the distance R is $E = (NE_\gamma)/S$, where S is the area of a sphere with

-185-

Table 10

Linear attenuation factors μ (1/cm) and layers of half attenuation $\underline{d}$(cm) for narrow parallel beams of γ-rays

Gamma-quantum energy Mev	Lead $\rho=11.3$ gr/cm^3		Iron $\rho=7.9$ gr/cm^3		Aluminum $\rho=2.7$ gr/cm^3		Concrete $\rho=2.3$ gr/cm^3		H$_2$O $\rho=1.0$ gr/cm^3		Air $\rho=0.001294$ gr/cm^3	
	μ	d	μ	d	μ	d	μ	d	μ	d	μ	d
0,5	1,72	0,4	0,66	1,05	0,228	3,04	0,194	3,56	0,0967	7,15	$1,11 \cdot 10^{-4}$	$6,2 \cdot 10^3$
1,0	0,79	0,88	0,47	1,47	0,166	4,17	0,141	4,90	0,0706	9,80	$0,81 \cdot 10^{-4}$	$8,5 \cdot 10^3$
1,5	0,58	1,19	0,38	1,82	0,137	5,05	0,116	5,95	0,0576	12,1	$0,66 \cdot 10^{-4}$	$10,5 \cdot 10^3$
2,0	0,51	1,35	0,33	2,10	0,117	5,90	0,100	6,93	0,0493	14,0	$0,57 \cdot 10^{-4}$	$12 \cdot 10^3$
3,0	0,46	1,50	0,28	2,48	0,094	7,40	0,080	8,65	0,0396	17,4	$0,45 \cdot 10^{-4}$	$15,5 \cdot 10^3$
4,0	0,47	1,48	0,26	2,66	0,084	8,25	0,071	9,75	0,0339	20,4	$0,39 \cdot 10^{-4}$	$18 \cdot 10^3$

radius $\underline{R}$ cm. Since $\underline{S} = 4 \times \underline{R}^2$, then $\underline{E} = (N\underline{E}\gamma)/ 4\pi R^2$, that is to say the intensity of radiation in a vacuum falls in inverse proportion to the square of the distance.

Taking the attenuation of the radiation by the medium into account, the intensity is equal to

$$ E = \frac{NE_1}{4\pi R^2} \left(\frac{1}{2} \right)^{\frac{x}{d}} $$

where $\underline{x}$ is the thickness of the material in the way of the radiation.

All the equations given earlier for the attenuation of the intensity of gamma radiation are valid when calculating for a direct beam of γ-quanta. In other words, they are derived on the assumption that all the scattered γ-quanta leave the confines of direct radiation.

When the intensity is calculated by equations for direct beams, however, it always proves to be smaller than the measured intensity of a wide beam, and the greater the thickness of the weakening layer, the greater the relative discrepancy between the electrical and measured intensities. This is because of the fact that as the wide beam of γ-radiation passes through the material, the proportion of single and multiple scattered γ-quanta increases all the time, and at great depths of penetration the entire beam consists for practical purposes of multiple scattered γ-quanta. Thus, the intensity of radiation calculated from the above equations without making allowance for the scattered radiation may turn out to be much too low.

The process of "accumulation" of scattered radiation proceeds particularly rapidly in media in which the Compton scattering is the predominant interaction process (like material such as air, water, soil, concrete, etc.).

In these media we have to make allowance for the scatter radiation, even if the thickness of the weakening layer is relatively slight. The method of calculating the scattered gamma radiation can be reduced to replacement of the stream of scattered quanta by an equivalent beam of direct quanta. It is usual to consider the streams of direct and scattered gamma quanta equivalent, provided they have the same ionizing effect in air[2].

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1)
The radiator is said to be a point source when its linear dimensions are small compared with the distance over which the intensity is determined.

-187-

A quantitative assessment of the scattered radiation can be made by introducing a correction multiple B, termed the accumulation factor, into the equations for intensity making allowance for the weakening by the medium. The factor B is a function of the energy of the primary gamma radiation, the thickness of the barrier and the type of weakening material.

Fig. 64 shows the dependence of the accumulation factor on the thickness of a weakening layer of water as an illustration of the need to take the scatter into account.
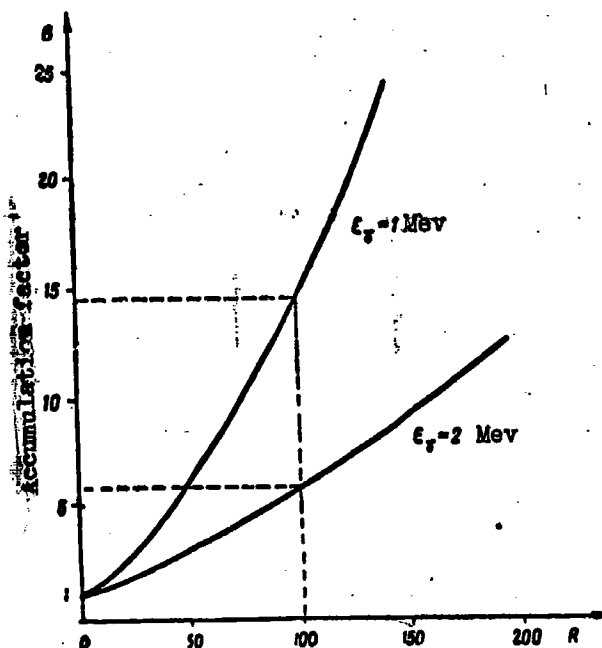
Fig. 64. Accumulation factor as function of thickness of a weakening layer of water.

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2)
     Or to be more exact, equal doses in air (for the definition of a dose see below).

-188-

It is clear from these graphs that when the thickness of the weakening layer of water is 1 m, the accumulation factors for the γ-quanta with energies of 1 Mev and 2 Mev are $B \leqq 15$ and $B \leqq 6$, respectively. In other words, given this weakening layer of water, the stream of radiation consists basically of scattered γ-quanta, disregard of which produces an underestimate of the radiation stream of a factor of 15 and 6, respectively.

Table 11 gives the thicknesses of concrete, iron, lead and water for wide beams of gamma radiation at different multiplicities of weakening. More detailed tables for the calculation of protective thicknesses can be found in the Reference Book on Radioactive Radiation and Protection (State Medical Publishing House, Moscow, 1956).

Table 11

Thickness of protective layers (in cm) of water, concrete, iron and lead for wide beams of gamma radiation for different multiplicities of weakening (energy of gamma quanta 1 Mev and 2 Mev).

Multiplicity of weakening	H_2O		Concrete		Iron		Lead	
	1 Mev	2 Mev	1 Mev	2 Mev	1 Mev	2 Mev	1 Mev	2 Mev
2	26	33	12,9	14,1	3,3	3,9	1,3	2,0
5	48	59	23,5	28,2	6,4	8,1	2,8	4,3
10	63	79	29,9	37,6	8,6	11,1	3,8	5,9
50	92	120	44,6	58,1	12,7	16,9	6,0	9,6
100	104	136	50,6	65,7	14,5	19,5	7,0	11,3

Interaction between neutrons and matter. Neutrons do not possess an electric charge and, as distinct from charged particles, when they pass through a substance, they do not interact with the electrons or the nuclei of the atoms. Hence neutrons may reach the atomic nucleus unimpeded, but at small distances from the nucleus (about 10^{-13} cm) there is a very strong interaction between the neutrons and the nucleus due to forces of attraction.

It has been found that the interaction between neutrons and the nucleus makes the latter scatter or capture (absorb) them. Thus, neutrons lose their energy or become absorbed when passing through a substance, solely through

collision with nuclei.

During scatter a neutron loses some of its kinetic energy (its velocity is reduced) and deviates from the original direction of motion. The nucleus which interacted with the neutron is conventionally called a "recoil" nucleus.

Scatter may be elastic or non-elastic. In elastic scatter all the neutron's absorbed energy is spent solely on imparting velocity to the recoil nucleus. This process can be regarded as a collision between two elastic bodies, for example, billiard balls.

In non-elastic scatter the neutron is first captured by the nucleus, forming a composite nucleus, after whih the latter emits a lower-energy neutron. Some of the absorbed energy is turned into the internal energy of the nucleus, that is to say the scattering nucleus becomes excited. The surplus energy is then emitted in the form of a gamma quantum.

As distinct from scatter, the capture of neutrons by nuclei is accompanied by nuclear reactions resulting in the formation of a new nucleus. These can be the following reactions:

1) the formation of a composite nucleus and its emission of 1 or more gamma quanta. This reaction is called radiation capture and is abbreviated to (n, γ)[1].

2) the decay of the compound nucleus by the emission of an alpha particle or a proton, that is to say a reaction of type (n, α) and $(n, \underline{p})$.

3) the emission of two neutrons by the compound nucleus, that is to say a reaction of the type $(n, 2\underline{n})$.

4) the fission of the compound nucleus into two new fragmentary nuclei, that is to say a reaction of the type $(n, \underline{f})$, where $\underline{f}$ indicates the fission of the nucleus.

New nuclei formed through the above-mentioned reactions may be either stable or radioactive.

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1) The first letter indicates the particle interaction with the nucleus (in our case the neutron) while the second letter stands for the particle escaping as a result of the reactions.

The probability of a neutron interaction with the atomic nuclei is usually described by the so-called effective cross-section σ which is measured in cm^2. σ is found experimentally. The significance of it is as follows. Let us assume a beam of neutrons with a cross-section of 1 cm impinges upon a fairly thin plate of thickness d. The total flux of neutrons striking the plate is Π. If n_0 is used to denote the number of nuclei contained in 1 cm^3 of plate, $n = n_0 d$ is the number of nuclei contained in the irradiated volume of the plate. The number of nuclei processes (for example, capture) in this volume of the plate can be determined from the equation

$$N = \Pi \, n_0 d\sigma$$

or

$$\sigma = \frac{N}{\Pi} \cdot \frac{1}{n} .$$

The quantity N/Π is numerically equal to the probability of interaction between a neutron and the substance, while n is the number of atomic nuclei per 1 cm of irradiated surface. Thus, σ, physically speaking, represents the probability of the neutron interacting with the substance, on condition that there is one nucleus for each square centimeter of radiated surface. The product $\sigma \cdot n_0 = \Sigma$ is conventionally called the macroscopic neutron cross-section. is measured in 1/cm. This quantity is similar to the attenuation factor μ for gamma radiation. σ ranges from 10^{-19} to 10^{-26} cm^2, hence it is convenient to express it in special units called barns: 1 barn = 10^{-24} cm^2 .

In accordance with the type of interactions, we distinguish the effective scatter cross-section σ_{sc} and the effective capture cross-section σ_{cap}. The total effective cross-section $\sigma = \sigma_{sc} + \sigma_{cap}$. The latter depends on the atomic number and the mass number of the target nuclei, as well as the energy of the neutron. In the case of rapid and intermediate neutrons the predominant type of interaction is scatter, that is to say for these neutrons σ_{sc} is many times greater than σ_{cap}. Hence the rapid and intermediate neutrons are scattered by the nuclei many times before being captured by them when they pass through the material. Each time the

neutron transmits some of its energy to the nucleus and thereby loses velocity. The reduction in the neutron's kinetic energy depends on the ratio of the mass of the nucleus and the neutron, as well as on the angle of scatter. Variation in the neutron energy increases as its mass approaches that of the nucleus and as the angle of scatter is increased.

In particular, during scatter on a proton (with a mass approximately equal to the mass of a neutron) the neutron loses all its energy at an angle of more than 90°. During scatter on heavy nuclei the variation in the neutron's energy is small, and can be assumed roughly that elastic scatter occurs without any loss of energy.

Table 12 shows the mean number of collisions required to turn the fast neutrons into slow ones for different substances.

Table 12

Mean number of collisions required to moderate neutrons

Materials	Mass number	No. of collisions
Hydrogen (light isotopes)...........................	1	18
Deuterium..	2	25
Lithium	7	67
Carbon...	12	114
Nitrogen...	14	132
Lead...	207	2000

The moderation continues until the energy of the neutron becomes equal to that of the thermal motion of the atoms in the medium. At room temperature this energy is 0.025 ev. Neutrons which attain this energy are known as thermal neutrons. Thus, the energy losses of a slow neutron during scatter continue until it turns into a thermal neutron.

The probability of scatter in the case of slow neutrons is more or less the same as for fast ones. But slow neutrons are captured by nuclei much more often than fast ones. This is a characteristic feature of the interaction between slow neutrons, as opposed to fast ones. The capture cross-section σ_{cap} of a slow neutron is dependent to a great extent on the mass number of the "target"

-192-

nucleus and varies in inverse proportion to its velocity. Hence the less the energy of the neutron, the greater the probability of its capture. Fig. 65 shows the variation in the effective capture cross-section of neutrons by boron as a function of their energy. The variation σ_γ is typical of light nuclei. Experiments show, however, that for nuclei with mass numbers $A > 100$ the effective capture cross-section for certain neutron energies jumped up and becomes much greater than the effective cross-section for the thermal neutrons. This phenomenon has been given the name of resonance capture. On the right hand side, Fig. 65 shows the effective cross-section σ_{cap} as a function of the neutron energy for cadmium. This graph shows that when the resonance of the energy is 0.18 ev, σ is roughly trebled, compared with the cross-section for the thermal neutron. Other elements, for example, indium, iron, gold, have two or more resonance peaks.

The capture of a slow neutron is usually accompanied by radiative capture. This reaction (n, γ) occurs both with light and heavy nuclei.
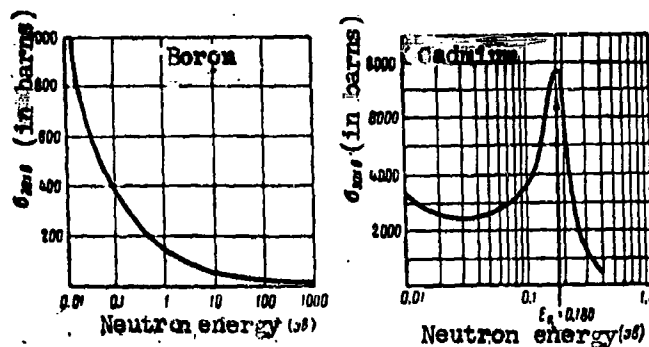
Fig. 65. Neutron capture cross-section for boron and cadmium.

Table 13 shows the effective cross-sections (in barns) for nuclei of different chemical elements.

Examples of slow neutron reactions (n, γ).

1) Light nucleus: $_1H^1 + _0n^1 \rightarrow [_1H^2]^* \rightarrow _1H^2 + \gamma$, that is to say during the capture of a neutron by an ordinary hydrogen nucleus, an excited deuterium nucleus is formed and gets rid

-193-

Table 13

Effective cross-sections of chemical elements (in barns)

Name of Element	Thermal Neutrons		Neutrons with Energy 1 Mev	
	σ cap.	$\sigma_{sc.}$	σ cap.	$\sigma_{sc.}$
Hydrogen...	0.33	38.0	No data	4.3
Carbon...	0.0045	4.8	Ditto	2.6
Nitrogen...	1.78	10.0	"	2.0
Oxygen...	less than 0,0002	4.2	"	8.0
Sodium...	0.50	4.0	0.00026	3.8
Aluminum...	0.21	1.4	0.00037	2.5
Silicon...	0.13	1.7	No data	4.5
Manganese...	12.7	2.3	0.0038	3.0
Cobalt...	35.4	5.0	0.011	3.1
Copper...	3.6	7.2	No data	3.5

of the excess energy by emitting a γ-quantum. The asterisk means that the compound nucleus is in an excited state.

2) Heavy nucleus: $_{79}Au^{197} + _0n^1 \rightarrow [_{79}Au^{198}]^* \rightarrow _{79}Au^{198} + \gamma$, that is to say during the capture of a slow neutron by the gold isotope 197, a new gold isotope - Au^{198} - is formed.

We should point out that the nuclei formed during neutron capture very often proved to be radioactive. For example, gold 198 is a beta or gamma-active isotope with a half-life $\underline{T} = 2.7$ days. This fact, as we shall discuss later on, is used in the recording of slow neutrons.

Reactions involving the capture of slow neutrons and accompanied by the emission of an alpha particle or a proton are encountered considerably less often. These reactions are only found in certain light nuclei. Conversely, fission reactions during the capture of slow neutrons are only natural for certain heavy nuclei (for example, U^{235}, Pu^{239}, U^{233}). Examples of slow neutron capture reactions with emission of an alpha particle and proton: emission of proton $_7N^{14} + _0n^1 \rightarrow _6C^{14} + _1H^1$, emission of an alpha particle $+ _0n^1 \rightarrow _3Li^7 + _2He^4$.

The capture of fast neutrons by nuclei is accompanied by reactions in which the emission of charged particles - protons and alpha particles - predominates. A reaction of the type (n,α) and (n, p) are restricted to elements with a relatively small mass number. Furthermore, these reactions are only possible when the neutron energies exceed a certain threshhold value. Hence the reactions (n,α) and (n, p) with fast neutrons are sometimes termed threshhold reactions. The threshhold energy of a neutron is a function of the isotope, but is always greater than 1 Mev.

Of the other reactions possible with fast neutrons, we can mention the $(n, 2n)$ and $(n, 3n)$ ractions. $(n, 2n)$ is only possible at threshhold values of the neutron energy $E > 9$ Mev. Fast neutron fission reactions are limited to a very small number of heavy nuclei U^{235}, U^{233}, Pu^{239}, U^{239}, Th^{233}, Pa^{231}, Np^{237}, and certain others.

Examples of capture reactions with fast neutrons accompanied)by the emission of an alpha particle or proton. Emission of a proton $_{15}P^{31} + _0n^1 \rightarrow _{14}Si^{31} + _1p^1$ (energy threshhold $E = 1.0$ Mev). Emission of alpha particles $_{13}Al^{27} + _0n^1 \rightarrow _{11}Na^{24} + _2He^4$ (emission threshhold $E = 3.3$ Mev).

As already pointed out the effective cross-section of a fast proton is many times less than the effective scatter cross-section. Hence the fast neutron usually completes its life cycle by becoming a slow neutron, rather than by getting captured.

Table 14 shows the characteristics of nuclear reactions involving neutron capture.

Being an electrically neutral particle, the neutron does not interact with electrons and does not therefore cause ionization itself.

The ionization of a material when neutrons pass through it is due to the "recoil nuclei", as well as alpha particles, protons and gamma radiation emitted during neutron capture. For example, the ionization of human tissue, which

-195-

Table 14

Characteristics of Nuclear Reaction Involving Capture of Neutrons

№ Symbol of reaction	Reaction equation	Neutrons with which reaction is most successful	Nuclei of which reaction is most successful	Comments
1 (n, γ)	$_zX^A + _0n^1 \rightarrow {}_zX^{A+1} + \gamma$	slow	light & heavy	Total energy of γ-ray quanta emitted about 7-10 Mev
2 (n, p)	$_zX^A + _0n^1 \rightarrow {}_{z-1}X^A + _1p^1$	fast	light	Exceptions are N^{14} plus He^3 which reactivate slow neutrons
3 (n, α)	$_zX^A + _0n^1 \rightarrow {}_{z-2}X^{A-3} + _2He^4$	slow	light	Exceptions are nuclei of isotopes Li^6, B^{10}, O^{12} which react with slow neutrons
4 (n, 2n)	$_zX^A + _0n^1 \rightarrow {}_zX^{A-1} + 2_0n^1$	fast	light & heavy	Usually only possible with neutrons of very high energy ($E > 9$ Mev).
5 (n, f)	Nucleus divides into two fragments with emission of 2-3 neutrons	slow	Heavy $Z > 92$ U^{235}, U^{233}, Pu^{239}	With fast neutrons at $E > 1$ Mev, U^{238}, Th^{233}, Pd^{231}, Np^{237}. also split up

contains hydrogen, oxygen, nitrogen, calcium and other elements, by slow neutrons is mainly due to gamma capture radiation occurring during the capture of neutrons by hydrogen nuclei as well as protons emitted during the capture of slow neutrons by nitrogen nuclei. The ionization of human tissue by fast neutrons is basically due to the recoil protons set in motion when they collide with fast neutrons.

A stream of neutrons, just as gamma radiation, is weakened by a material through two processes: scatter and absorption (capture). Hence the weakening of a neutron stream and gamma radiation are similar in nature.

In particular, a narrow, parallel beams of neutrons is weakened exponentially as

$$\Pi = \Pi_0 \, e^{-\Sigma R},$$

where Π_0 is the neutron flux just before entry into the obstacle;

Π is the neutron flux beyond the obstacle;

R is the thickness of the obstacle;

Σ is the total macroscopic neutron cross-section.

The quantity $\lambda = 1/\Sigma$ is called the mean path of a neutron in a substance. Numerically λ is equal to a layer of substance during passage through which the neutron flux is weakened e times.

Table 15 gives the values of Σ and λ for neutrons with an energy of 1 Mev when propagated through different materials.

Table 15

Σ and λ for neutrons with energy of 1 Mev

Material	Water	Aluminum	Iron	Lead
$\Sigma \, (1/\text{cm})$	0,550	0,150	0,170	0,178
$\lambda \, (\text{cm})$	1,83	6,7	5,90	5,6

The equation $\Pi = \Pi_0 \, e^{-\Sigma R}$ does not take scattered neutrons into account, that is to say it is assumed when using it that every scattered neutron is thrown clear of the beam.

In actual fact, the neutrons which are scattered at small angles remain

-197-

in the beam, increasing the total neutron flux. To take the scattered neutrons into account, the equation can be supplemented with a multiplier - the accumulation factor which is a function of the initial energy of the neutron, the type of weakening substance and the thickness of the layer. At the present time, however, there are no really reliable methods of calculating the accumulation factor for neutrons. Hence, we usually find the weakening of the neutron flux for each material on the basis of experiment.

3. Unit of measurement of ionizing effect of radiation

As has already been mentioned, the harmful biological effect of nuclear radiation is due to its power to ionize atoms and molecules making up human tissue. In a number of cases the ionization causes decay and the formation of new molecules, and therefore to the change in the properties of vitally important parts of cells. The mechanism by which nuclear radiation has a biological effect on the human organism, it cannot be said to have yet been completely explained. Most investigators consider that a large part is played by ionization of the water molecules contained in the living tissue (there is as much as 70% or more water in the human organism). Thus, it has been experimentally shown that destruction of dried (anhydrous) viruses, bacterial spores and seeds is caused by irradiation doses thousands of times greater than for the aqueous state.

When an electron is knocked out of a water molecule, we obtain a positive H_2O^+ ion; the ejected electron "sticks" to another molecule, forming a negative ion H_2O^-. The ions formed are unstable and decompose (dissociate) according to the following pattern

$$H_2O^+ \rightarrow H^+ + OH$$
$$H_2O^- \rightarrow HO^- + H.$$
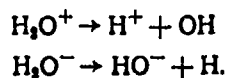
Apart from the dissociation the reverse process also occurs - the formation of hydrogen molecules and hydrogen peroxide

$$H + H \rightarrow H_2$$
$$OH + OH \rightarrow H_2O_2.$$

-198-
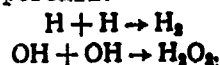
Hydrogen peroxide and the decomposition products (H, OH, O), even in micro-
scopic quantities have a harmful effect on living tissue and cause a peculiar
kind of chemical poisoning.

The selection of the unit to measure the ionizing effect of nuclear
radiation is closely bo und up with evaluation of the harmful biological effect.

The degree of ionization of any substance is characterized by the number of
pairs of ions formed by radioactive radiation in 1 cm or 1 gram of that substance.
A definite amount of energy is spent on the formation of one pair of ions in each
substance, and this amount, as we already know, is called the work function. So
the ionization produced can be used to gain an idea of the absorbed energy, and
vice versa. The number of pairs of ions formed in 1 cm^3 of a material is equal
to the ratio of the energy absorbed by this amount of material in 1 cm and the
mean work function. For example, if absorbed energy in 1 cm^3 of air is 100 · 10^6
ev, then $(100 \cdot 10^6 \text{ ev})/(32.5 \text{ ev}) \approx 3 \cdot 10^6$ pairs of ions are formed in a cm^3.

The radiation energy absorbed by 1 cm of material is termed the
radiation dose. The greater the dose, the greater the degree of ionization of the
material. For gamma rays possessing a constant intensity, the radiation dose $\underline{D}$
is equal to

$$D = \mu_a E t,$$

where $\underline{t}$ is the irradiation time;

$\underline{E}$ is the radiation intensity;

μ_a is the linear absorption factor of the gamma rays in the material.

The absorption of the gamma ray energy, that is to say its change into
the kinetic energy of the fast secondary electrons ionizing the medium is due to
photoelectric absorption, the absorption of the Compton effect energy and the
formation of pairs.

We should point out that the factor μ_a is always less than the attenuation
factor μ, since the scattered gamma quanta carry energy away from the beam with-
out it being absorbed by the medium.

-199-

Table 16 shows the factor $\sum_a$ for air as a function of the gamma quantum energy.

Factor $\sum_a$ for air under normal conditions ($\rho = 0.00129$ g/cm^3)

E_γ (Mev)	0.1	0.5	1	2	4	6
μ_a (1/cm)	$3.0 \cdot 10^{-5}$	$3.8 \cdot 10^{-5}$	$3.56 \cdot 10^{-5}$	$3.04 \cdot 10^{-5}$	$2.72 \cdot 10^{-5}$	$2.35 \cdot 10^{-5}$

The equation for $\underline{D}$ suggests that the size of the dose increases in direct proportion to the radiation intensity and irradiation time. Furthermore, terms of μ_a depends on the energy on the gamma quantum, the density of the irradiated material and the atomic number $\underline{Z}$ of the latter.

Since the dose depends/on the properties of the medium, it is quite natural to compare the ionizing effect of radiation according to the dose created by it in a particular medium. Air has been selected as this medium and the unit of dose itself is determined from the degree of ionization of air. This unit is termed the roentgen in honor of the famous German physicist Roentgen, who discovered x-rays.

The roentgen is a dose of x- or gamma radiation such that the ions formed with one sign in 1 cm of dry air under normal conditions[1] possess a total charge of one electrostatic unit of electricity (CGSE).

The charge on the electron is $4.8 \cdot 10^{-10}$ CGSE, so that if we assume that every ion has a charge of one electron, the number of pairs of ions formed during a dose of one roentgen in 1 cm of air is $1/(4.8 \cdot 10^{-10}) = 2.08 \cdot 10^{9}$, that is to say almost 2 billion.

This gives us another definition of the roentgen: the roentgen is a

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1) Temperature 0°C and pressure 760 mm Hg.

radiation dose such that one cubic centimeter of air under normal conditions forms approximately 2 billion pairs of ions, each of which possesses a charge equal to that of the electron.

It is not difficult to find the absorbed energy corresponding to a dose of 1 roentgen. The energy spent on forming one pair of ions in air is 32×5 ev; a dose of one roentgen produces 2.08 billion pairs of ions, hence the absorbed radiation energy in 1 cm is equal to 2.08 billion pairs of ions X 32.5 ev = 68 billion electron volts $(68 \cdot 10^3$ Mev$)$.

Calculation of the dose from the degree of ionization of air expressed in roentgens is due, first, to the fact that the degree of ionization of air is the simplest to measure and, second, the energy is absorbed by 1 cm^3 of living tissue and 1 cm^3 of air are proportional to each other over a wide range of gamma quantum energies. The proportionality factor is equal to the ratio of densities of the tissue and air. This fact enables us to evaluate the degree of ionization of living tissue from the ionization of air without bothering about the energy of the gamma quanta.

The ratio of the density of tissue to the density of air is 770, so if a dose of 1 roentgen is measured in air, living tissue receives a dose 770 times greater. But this conversion is not usually made, and the degree of ionization of tissue is judged directly from the dose measured in air.

In the equation given above the dose is measured in energy units per 1 cm . One roentgen corresponds to the absorption by 1 cm^3 of air of $68 \cdot 10^3$ Mev gamma radiation, so tha t if the right-hand side of the equation is divided by this quantity , we obtain an expression for the dose in roentgens.

$$D = \frac{\mu_a \, Et}{68 \cdot 10^3} = 0,147 \cdot 10^{-4} \, \mu_a \, Et.$$

In this equation the intensity E should be expressed in Mev/cm^2 sec and the time t in seconds.

The dose accumulated in one unit of time is termed the **dose rate**. If the

dose rate P is constant, $\underline{P} = D/\underline{t} = 0.147 \ 10^{-4} \mu_\lambda \underline{E}$ roentgen/sec. It is conventional to measure the dose rate in roentgens per hour; since 1 hour equals 3600 seconds,

$$P = 0.147 \cdot 10^{-4} \ 3600 \mu_s \ E = 0.0525 \mu_s \cdot \underline{E}_\gamma \ J \ \text{roentgen/hour}$$

where $\underline{E}_\gamma$ is the energy of the quantum in Mev;

$\underline{J}$ is the gamma quantum flux through 1 cm^2 per sec.

Let us calculate the dose rate created by a second-long flux of gamma quanta $\underline{J} = 1000$ quanta/sec cm^2 with quantum energy $\underline{E}_\gamma = 1$ Mev. Table 16 for air gives us $\mu_\lambda = 3.56 \cdot 10^{-5}$ 1/cm. Then, $\underline{P} = 0.0525 \mu_\lambda \underline{E}_\gamma \underline{J} = 0.0525 \times 3.56 \cdot 10^{-5} \cdot 1 \cdot 1000 = 19 \cdot 10^{-4}$ roentgen/hour.

Finally, the flux of gamma quanta through 1 cm^2 required to produce a dose of one roentgen can be found from the very simple equation

$$\Pi \approx \frac{2 \cdot 10^9}{E_\gamma} \ \text{quantum/cm}^2$$

where $\underline{E}_\gamma$ is measured in megaelectron volts.

If, for example, $\underline{E}_\gamma = 1$ Mev, $2 \cdot 10^9$ quanta must pass through 1 cm^2 of irradiated surface in order to produce a dose of one roentgen.

To measure the ionizing effect of charged particles (beta, alpha particles and protons) and neutrons, we use a unit which has come to be called the "physical roentgen equivalent" (rep). The same degree of ionization of air is produced by doses of 1 rep and 1 roentgen of gamma radiation.

But the same amount of ionization of air due to alpha, beta or gamma radiation and neutrons has different biological effects. In other words, a dose of 1 roentgen from gamma radiation is not equivalent in biological effect to a dose, let us say, of 1 rep from a neutron flux. This is due to the different natures of ionization of different types of radiation. Hence, to assess the biological effect, we use a special unit - the biological roentgen equivalent (re); 1 bre corresponds to the effect of particles equal to the biological effect

-202-

of 1 roentgen of gamma radiation.

Table 17 shows the relative biological effectiveness of different kinds of radiation for the same degree of ionization of air. It follows from this table that, given the same dose in reps, the most biologically harmful radiation is alpha radiation. This is due to the fact that alpha particles possess the greatest ionizing ability. Fast neutrons exhibit much the same biological effect as protons, since the ionization of living tissue by fast neutrons is caused by the recoil protons. X-rays, gamma radiation and beta particles exhibit the same biological harmfullness and ionization of a medium by these types of radiation is roughly the same in nature since it is due to the effect of secondary electrons.

Table 17
Relative biological effect of different types of radiation for the same degree of ionization of air.

Radiation	Roentgen or rep	Relative biological effectiveness
X-rays...	1	1
Gamma rays...	1	1
Beta particles...	1	1
Thermal neutrons...	1	5
Fast neutrons...	1	10
Protons...	1	10
Alpha particles...	1	20

In order to estimate the biological effect of neutrons we have to know the neutron flux through 1 cm^2 creating a dose of 1 bre. These values are shown in Table 18 as a function of the neutron energy.

The damaging effect of nuclear radiation will be discussed in greater detail later on. For the moment we will give some examples to enable readers to understand the roentgen as a unit of dosage.

We are all continuously subjected to the effect of cosmic and gamma

Table 18

Neutron flux creating a dose of 1 bre.

Neutron energy	Neutron flow through 1 cm^2 creating dose of 1 bre
Thermal	10^9
5 kev	$8 \cdot 10^8$
0,5 Mav.	$4 \cdot 10^7$
2,5 Mev	$1,8 \cdot 10^7$

radiation stemming from the natural contamination of soil, air and water by radioactive matter. The dose produced by the radiation is not greater than 0.1 roentgen per year. Once or more times a year we all have an x-ray photograph taken of our chests; the dose received here is about 0.05 roentgens per examination.

The luminous dial of a wristwatch is coated with a mixture consisting of zinc sulphate and a minute quantity of radium (about 0.000001 g). The radium emits gamma rays which pass through the casing of the watch and create a dose of about 0.04 roentgens per year in the human body, (as an average).

These three examples illustrate doses which do not endanger people's health.

4. Methods of detecting and measuring nuclear radiation

Techniques used to measure and detect nuclear radiation have come to be called dosimetry. Their symmetry includes the two following principal types of measurement.

1) Roentgen metering is the measurement of the ionizing effect of nuclear radiation (in roentgens).

2) Radiometry is the calculation of the activity of nuclear radiation sources, the measurement of particle flux and the degree of contamination of different surfaces and volumes by radioactive substances.

Methods of recording and measuring nuclear radiation are usually based on the power of the radiation to ionize the medium through which it is propagated.

In its turn, the ionization may cause a whole number of physical or chemical changes in the medium. In many cases these changes may be determined comparatively easily and measured quantitatively. Changes due to nuclear radiation include the creation of an ion current in gases, the creation of an image on film, change in the color of chemical solutions and solids (for example, glass), luminescence of certain materials, variation in the resistance of semiconductors and so forth.

Ionization chambers. Gas which is insulated from the ionizing effect will not conduct any electric current. This is because the current carriers in the gas are ions and free electrons which are only produced in the gas through the action of an outside ionizer.

The ability of gases to become electric conductors when acted on by nuclear radiation is the working principle of most contemporary dosimetric instruments. The sensing elements in these instruments are ionization chambers and gas-discharge counters.

The ionization chamber consists of two mutually insulated electrodes, on which a co n stant voltage is impressed.

The simplest type of ionization chamber (Fig. 66) consists of two metal plates in parallel - the electrodes. The space between them, which is called the working volume of the chamber, is filled with a gas, usually air.

The nuclear radiation passing through the working volume creates positive and negative ions.

When there is no potential difference between the plates, the ions, just as any other neutral atom or gas molecule, are in a state of chaotic thermal motion. If the voltage is applied across the plates, motion of the ions becomes directed: the positive ions approach the negative electrode - the cathode - as a result of the electric field, and the negative ions move towards the positive based charge - the anode. The greater the voltage and the smaller the distance between the plates, the greater the velocity of motion of the ions.

The directional motion of the charged particles is the actual cause of

-206-

the ionizing current in the chamber circuit. The ionisation current is equal to the total electric charge carried by the ions to the surface of the electrode in one second. The larger the number of ions gathering at the electrodes, the greater the current. The current can be recorded by means of an electro-measuring device plugged into the chamber circuit. There are no ions in the working volume of the chamber beyond the area affected by the radiation, so the device indicates no current (the needle points to zero).
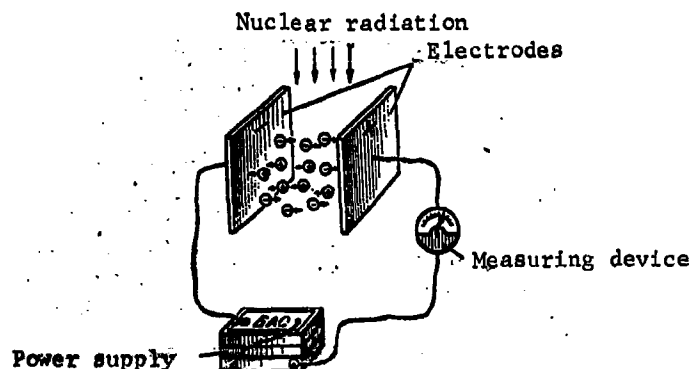
Fig. 66. Working principle of ionization chamber.

Apart from ionization, the reverse process - combination - occurs simultaneously in the gas. Recombination is the joining of ions of opposite sign and results in the formation of a neutral atom or molecule. On account of recombination, not all ions or electrons formed by the nuclear radiation have time to reach the electrodes. Recombination has a particularly marked effect at low voltages. Here the velocity of ionic motion is relatively low and most of the ions recombine while in motion, only a few reaching the electrodes.

As the voltage is stepped up, the velocity of motion of ions and electrons increases and this leads to a reduction in the time taken to reach the electrodes and also in the probability of their recombination. As the number of recombining ions decreases, the number of those reaching the electrodes is increased, and there is then a greater ionization current. But there comes a moment when the increase in voltage no longer produces an increase in the current

this is due to the fact that virtually all ions have gathered at the electrodes.

A current such that virtually all ions formed in the chamber as a result of the ionizing radiation gather at electrodes is called a saturation current.

Ionization chambers usually operate in the region of saturation; the saturated current is proportional to the number of ions formed and may therefore be used as a measuring stick for the ionizing effect of the radiation. These chambers are divided into two types according to their purpose:

1) integrating ionization chambers which are used to measure total ionization caused by the passage of a visible number of ionizing particles through the chamber;

2) counting chambers which are used to record and determine the ionizing effect of a particular ionizing particle (for example, an alpha particle) which has reached the working volume of the chamber.

In the integrating chamber the saturation current can be used to measure the dose rate which is proportional to the number of pairs of ions forming in 1 cm^3 per unit time. To measure the dose rate the scale of the electric measuring device has to be graduated in units of dose rate (roentgen/hour), and not in units of current.

Despite the apparent simplicity of the construction of an ionization chamber, serious difficulties involving the measurement of weak ionization current are encountered when manufacturing and adjusting chambers of this type. This is because in ionization chambers the ionization current is a small, even if the radiation is comparatively powerful. For example, if the working volume of the chamber is 1 liter, a dose rate of one roentgen an hour does not produce current of more than one ten billionth of an ampere. Such small currents can only be measured by conventional measuring devices after preamplification by electronic amplifiers.

The size and shape of the chamber electrodes differs according to its purpose. There are chambers in which the electrodes are made in the form of two parallel plates, concentric spheres or other shapes. Electrodes usually made of bakelite, plexiglass or some other light material and are coated with a thin layer of graphite. Chamber electrodes are often made of conducting plastics.

Since beta and particularly alpha particles possess low penetrating power, the ionization chamber used to measure these radiations should have a window covered with a thin film through which the particles can enter the working volume. Furthermore, when alpha radiation is measured, the chamber must be brought right up to the radiation source, or better still, the source should be placed in the actual working volume, since alpha particles are strongly absorbed by air around the instrument.

Gamma rays possess high penetrating power; they pass through the chamber walls several milimeters thick without appreciable absorption, hence a chamber with walls of this kind is virtually open on all sides to the penetration of gamma quanta.

The chamber walls have a great effect on the measurement of the ionization effect of gamma rays. As we already know, a substance is ionized by gamma quanta on account of the secondary fast electrons created when the gamma quanta interact with the atoms of the substance. In the chamber these secondary electrons are formed both in the gas filling the working volume as well as in the walls. The ionizing effect of secondary electrons detached by the gamma quanta from the atoms of the wall is usually known as the "wall effect". Naturally, only those secondary electrons get into the working volume which are created in the surface layer of the wall. The thickness of this layer is not greater than the path of the electrons in the wall, that is to say it is not more than several milimeters, in the case of a wall made of plastic. But since the density of the wall material is thousands of times greater than that of the gas, the number of secondary electrons formed by gamma radiation in the walls and reaching the working volume is hundreds of times greater than the number of secondary electrons created in the actual gas. This means that the electrons knocked out of the wall by the gamma

quanta produce the principal ionization in the working volume and therefore determine the ionization current.

The wall effect makes it necessary to manufacture chamber walls from so-called air-equivalent materials. Among such materials are bakelite, plexiglass and other lightweight substances. The radiation dose per gram of air in these materials coincide above a wide range of gamma quantum energy, so that the ionization is caused by the effect of a wall of air-equivalent material and is proportional to the ionization of air. This enables us to make chambers with walls of light materials to measure gamma radiation doses made up of gamma quanta of different energies directly in roentgens.

Gas-discharge counters. As has already been mentioned counting chambers can be used to record individual radiation particles passing through the working volume since every particle which creates an ion produces a jump (pulse) in the electric circuit current. In ionization chambers, however, the current pulses produced by individual particles are very small and require complex amplifiers to measure them. Hence ionization chambers are chiefly used to measure the total ionization effect due to the passage of a large number of particles through the working volume.

To record individual particles or to measure dose rates of gamma radiation, extensive use is now made of gas discharge counters.

If we impress a voltage of several thousand volts on the electrodes of the ionization chamber shown in Fig. 66, it can be turned into a gas-discharge counter. As the voltage is increased, the velocity of the electrons moving towards positive electrode is stepped up. At a certain voltage the electron velocity may attain such a point that if the electrons encounter neutral atoms or molecules, they themselves may ionize them. This effect is termed impact ionization. Impact ionization makes the initial electron after collision with a neutral atom produce another electron and a positive ion. These electrons acquire high velocities and in turn produce new ions and electrons, and so on

-210-

and so on. By the time the initial electron has collided for the tenth time there are a thousand ions. The number of ions and electrons increases like a snowball. In this way a small number of primary ions created by an ionizing particle is multiplied millions of times and this produces a sharp increase in the current, compared with the current produced by the same ionizing particle in an ionizing chamber.
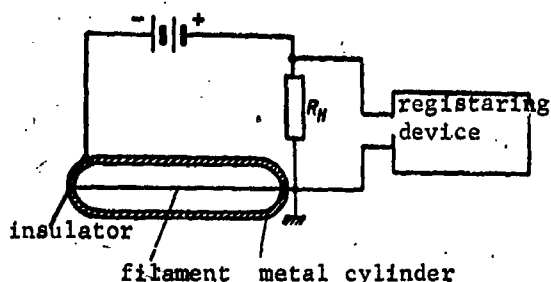
Fig. 67. Working principle of gas discharge counter.

Fig. 67 shows the construction of a gas discharge counter. It usually consists of a thin-walled metal cylinder with a metal filament running along the axis. The filament is the anode and the cylinder is the cathode. The space between the cylinder and the filament is filled with gas at low pressure. Inert gases are usually used as the fillers (argon, neon or mixtures of them) and the electrons are the negative ions in them. The choice of these gases is due to the fact that by possessing a mass several thousand times smaller than the ions, the electrons are more mobile and can more easily be boosted to the velocities at which impact-ionization begins. The use of a thin metal filament with a radius of tenths of a milimeter as the anode makes it possible to considerably reduce the voltage at which impact ionization begins. While this voltage is several thousand volts for plane electrodes, it is several hundred volts for cylindrical electrodes, so the gas counters are almost always cylindrical.

Let us see how the counter can be used to record nuclear particles. If there is no nuclear radiation, the gas filling the counter consists of neutral atoms and does not conduct current; the circuit is broken and no current flows

-211-

through it. Let us assume that an ionizing particle gets inside the cylinder and creates at least one pair of ions on the way. The electric field causes the positive ion to rush towards the cathode and the electron to travel towards the filament (anode). The electron is quickly boosted to a velocity at which it begins to ionize any neutral atoms or gas molecules in the way by its impact. As a result a complete avalanche of electrons and positive ions is produced near the filament. Over a period of about one millionth of a second all the electrons collect at the filament. The relatively heavy, and therefore rather immobile positive ions hardly budge at all during this time. At the next discharge stage the ions move towards the cathode, the process taking approximately one ten thousandth of a second. The ions which reach the cathode extract electrons from it, become neutralized, that is to say, turn into neutral gas atoms and molecules.

The motion of the ions and electrons produces a current pulse in the counter circuit, and as it passes through the load resistance this current produces a voltage. In this way, the particle passing through the counter is recorded in the form of a voltage signal.

As soon as it has been amplified, the voltage is fed to a recording device which automatically counts the signals or in other words, the particles passing through the working volume of the counter.

Until the positive ions are some way away from the anode, the next avalanche of ions in the counter cannot occur since the positively charged "jacket" of ions sharply reduces the strength of the electric field close to the filament. So as long as the ions remained close to the anode, the counter is "indifferent" to any new particle.

The time taken by the positive ions to gather at the cathode is usually termed the dead time. The dead time for gas counters is relatively high - 0.0001 sec; this is a major shortcoming in them since many of them may go unrecorded if the flux is intense.

According to the voltage impressed upon the electrodes, the counter

-212-

may work by proportional amplification (proportional counters) or by independent discharge.

In proportional counters, which work at comparatively low feed voltages, the amplitude of the recorded pulses is proportional to the charge on the ions created by the ionizing particle. Hence these counters may be used both to count particles as well as to determine their ionizing effect. In proportional counters, however, the ratio of the total number of ions produced to theinitial number of ions formed by the original ionizing particles is comparatively small (up to 10,000), so they are chiefly used to record particles with high ioniting ability (alpha particles).

When the feed voltage is fairly high (300 - 1000 volts, according to the design of the counter), the counter operates under conditions of independent electric discharge which is characterized by the fact there is no dependence between the total number of ions produced and the original ionization. Counters working this way are now called geiger-mueller counters. In these counters the amplitude of the recorded voltage pulse does not depend on the original ionization; in the case of particles with low and high ionizing ability it remains the same. That is why geiger-mueller counters cannot be used directly for measuring the ionizig effect of radiation. Nevertheless, they are infinitely more sensitive thanproportional counters and that is why they are widely used to measure beta particles and gamma quantum fluxes.

A very important characteristic of gas counters is their efficiency. The efficiency of a counter must give the ratio of the number of particles causing a discharge to the total number of particles entering the counter. The eff-iciency of gas counters with respect to alpha and beta particles is close to 100%. The effectiveness of counters with respect to gamma quanta ranges from 0.2 to 1.5%.

Counters, just as the ionization chambers, record the gamma quanta chiefly by means of the secondary electrons knocked out of the counter walls by the gamma quanta. The knocked out electrons fall into the working volume and

cause an electric discharge. The counter efficiency is a function of the gamma quantum energy. For example, in a counter with an aluminum cathode, the efficiency is stepped up from 0.2% to 1.2% when the gamma quantum energy is raised from 0.2 to 2 Mev. Thus, if the energy of the recorded gamma quanta is unknown, the errors made in determining the number of gamma quanta passing through the counter may be very high.

The counters are designed in accordance with their basic purpose.

Counters used to measure alpha particle streams should have a window covered with a thin mica film about 0.001 cm thick, in which there is no great decrease in the energy of the particles. The window is located at the end of the counter and that is why instruments of this type are called end-window counters.

The working voltage fed to the alpha counter is such that it operates in the proportional region. The pulses due to the alpha particles then are 30 - 50 times greater than those produced by beta particles or gamma quanta. When the voltage has been raised to a certain point, the counter switches to the independent discharge region, and can be used to count beta particles and gamma quanta.

End-window counters are also used to record beta particle fluxes. In this case the thickness of the mica window is about 0.005 cm. A film of this kind does not absorb very many beta particles, even if their energy is low (up to 0.05 - 0.1 Mev).

To record a flux of beta particles with comparatively high energy (greater than 0.5 - 1 Mev), use is made of cylindrical counters, the walls of which are made of aluminum or steel about 0.01 cm thick. Such counters are more sensitive than end-window ones, since their working surface is considerably greater and they are now widely used in field dosimetry. To record gamma quantum fluxes we use cylindrically shaped counters with walls several milimeters thick. Cylindrical counters with extra covers in which the beta particles are totally absorbed are usually used for the measurement of a gamma flux.

<u>Photographic indicators</u>. Photographic films have come to be used for measuring gamma radiation doses. As distinct from alpha particles, when gamma quanta act on photographic emulsion, they do not form traces but cause overall darkening in the film when developed. The degree of darkening (density) of the film is proportional to the radiation dose. Film can be used to measure doses of gamma radiation ranging from tenths of a roentgen to several tens of thousands of roentgens, but the film is of different sensitivity in different cases. The density of the film is determined by means of special devices which have come to be called densitometers to determine the dose in roentgens, the density of the film is compared with the darkening of another film which has been exposed to a known dose of gamma radiation.

Comparison of the darkening densities of the two films can only be made if they have been developed under exactly the same conditions. They have to be developed in the same tank, at the same concentration and temperature of the developer and also for the same amount of time.

The relationship between the density and the dose for a certain type of photographic film is shown in Fig. 68. Up to a certain dose D_1 the density is directly proportional to the dose D, after which the density increases more slowly than the dose, and finally, beginning at D_2, there is a fall in the density of the darkening as the dose increases. This latter fact may be the cause of gross errors in measuring doses, since there can be two values for the same darkening density. Hence the sensitivity of the film should be selected in such a way as to avoid work in the last segment of the curve showing the density as a function of dose.

It has been found that if the film is subjected to the action of gamma quanta with energy less than 0.3 Mev, the density of the film is not only a function of the dose, but also the hardness of the radiation, that is to say the energy of the quanta. In other words, the same doses of radiation with different gamma quanta energies produce different degrees of darkening of the films. This fact is

-215-

a major shortcoming in photographic indicators, since it may lead to gross errors in the measurement of doses of mixedradiation containing gamma quanta with energy less than 0.3 Mev.
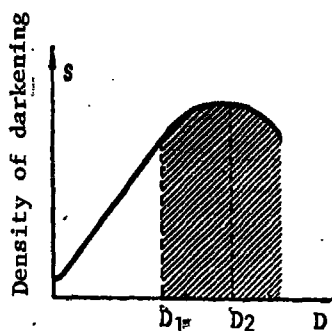
Fig. 68. Density of darkening of photographic film as function of dose.

If the energy of the gamma quanta is greater than 0.3 Mev, the degree of darkening of the film, though remaining proportional to the dose, no longer depends upon the energy of the gamma quantum. To eliminate the dependence of density on energy, the photographic film is enclosed in lead or cadmium sheets about 1 mm thick on both sides. These metal filters allow through high energy gamma quanta without marked absorption and greatly weaken the gamma radiation with gammaquanta energies less than 0.3 Mev. This smooths out the relationship between the density of the film and the energy of the gamma quanta to a considerable extent, or in other words, the density for the same radiation dose remains constant over a wide range of energies.

Chemical indicators [1]. Over the last few years another important method of measuring gamma radiation and fast neutron fluxes has been developed. It is based on the chemical effect of nuclear radiation. It has been found that when chlorinated hydrocarbons (chlorphen, trichloroethylene) and certain other chemical compounds are irradiated, oxygen is formed in a quantity which is proportional to the gamma radiation or neutron dose within wide limits. The amount of oxygen formed can most easily be determined with color indicators, that is to say substances the hue of which depends on the concentration of oxygen given off. Very simple dose indicators can be constructed on the basis of this

-216-

effect. The chemical indicator is a glass ampoule filled with a liquid consisting of chlorinated hydrocarbons and an aqueous solution of a color indicator. The magnitude of the dose is found by comparing the color of the solution with that of control indicators, that is to say indicators irradiated with known doses. A colorimeter is used to determine the hue of the solution. Simplicity in the handling of chemical indicators, compared with photographic films, makes the method a much more promising one.

Chemical indicators make it possible to measure doses over a wide range (up to a million roentgens), but their sensitivity to small doses is very low and that is why they are mainly used at the present time for measuring large doses (tens and hundreds of roentgens).

Scintillation counters. Back at the beginning of the twentieth century it was found that certain materials begin to luminesce when acted upon by radioactive radiation. These include zinc sulphide, sodium iodide, naphthalene crystals, anthracene and many other solids and liquids.

The passage of alpha, beta particles and gamma quanta through luminescent materials causes a flash of light called a scintillation.

The greater the ionizing power of the particle, the more ionized atoms it creates and the brighter the flash of light. The intensity of the scintillation is proportional to the intensity of the nuclear radiation, hence by counting the number of flashes we can determine the particle flux through the luminescent material.

Fig. 69 shows a simplified diagram of a scintillation counter. The counter consists of a luminescent crystal (luminophore) transforming the radioactive radiation into light energy, and a photomultiplier recording the separate flashes of light in the form of current pulses. The photomultiplier is a cylindrical glass container pumped free of air. Inside is an electrode system. The first electrode is the photocathode attached to the inside of the surface of the container in the form of a thin semitransparent layer which readily emits

electrons when subjected to light. The present-day photomultipliers used for scintillation counters usually have antimony - cesium photocathodes, since of all the known photocathodes these posses the maximum quantum yield. The quantum yield is the number of electrons detached by one quantum of light when it impinges upon a photocathode. Behind the photocathode is the focusing electrode, made in the form of a plate with a circular opening. Then comes a row of electrodes known as emitters, and finally the anode. The cathode works at the lowest potential, and each subsequent electrode (emitter) receives a voltage approximately 100 volts higher than theone before. The anode works at the greatest potential; the potential differente between the anode and the cathode in modern photomultipliers ranges from 800 to 2000 volts.

As the particle of nuclear radiation passes through the luminophore, it causes a very brief flash of light in it. Some of the photons reach the photocathode through the light pipe and knock out electrons. The total number of electrons produced during the passage of one ionizing particle through the crystal does not exceed a thousand, and the total charge constitutes a negligibly small value ($\sim 10^{16}$ coulomb). This charge can neither be measured nor even detected without further amplification, except with exceptional difficulty. The emitters in the photomultiplier make it possible to "multiply" the electrons several of hundreds of thousand times. The working principle of the photomultiplier is as follows. The electrons knocked out of the photocathode are boosted by the electric field and are focused on the first emitter (1E) by means of the focusing electrode. Every electron reaching the emitter knocks out several other electrons. The electrons escaping from the first emitter are boosted by the electric field and move towards the second emitter where the same thing happens again. The multiplication of electrons continues at all the subsequent emitters. The electron flux from the last emitter in the series is gathered at the anode. The total amplificationfactor of the photomultiplier is $K \neq \sigma^n$, where σ is the multiplication factor of the electrons by one emitter,

-218-

and $\underline{n}$ is the total number of emitters.

In present-day photomultipliers the multiplication factor σ is approximately four when the potential difference between the neighboring emitters is 100 volts. Hence the photomultiplier with ten emitters has a total amplification factor $\underline{K} = \sigma^{n} = 4^{10} \approx 10^{6}$ times.

Electrons impinging upon the anode slow down through the load resistance R and create in the latter a brief voltage pulse which may be comparatively easily measured.
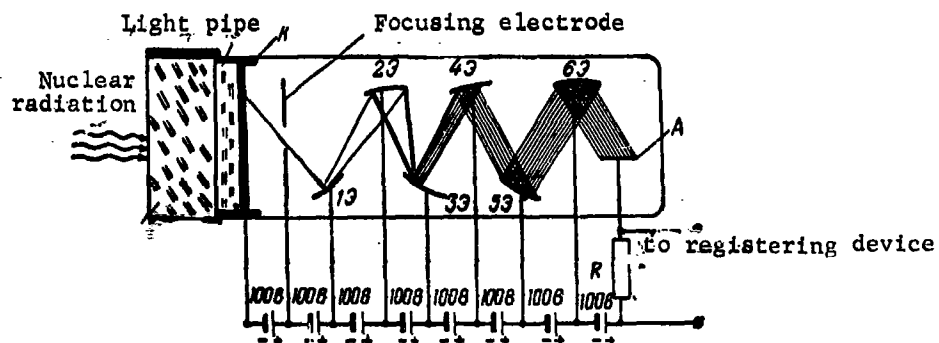
Fig. 69.   Diagram of scintillation counter

Thus, the passage of an ionizing particle through the crystal in the scintillation counter is detected by a brief voltage pulse. The amplitude of the voltage in these counters, as distinct from independent gas discharge particles, is proportional to the ionizing power of the radioactive particles, hence scintillation counters can be directly used both for counting particles as well as for measuring the ionizing effect of radiation. A scintillation counter has a high recording efficiency for all typesof radioactive radiation, and in the case of gamma rays this approaches 50% or more. Furthermore, these counters have a very short dead time. The dead time, which is conditioned by the length of the flash in the crystal, (10^{-5} - 10^{-8} sec) and the time taken by the electron to pass

-219-

through the multiplier (10^{-4} sec) is slightly less than in gas counters.

At the present time we know of a large number of luminescent solids and liquids which can be used in scintillation counters. The most suitable ones for this purpose are organic crystals of the "sodium-iodine","cesium-iodine" type, organic crystals of the "stilben" and "anthracene" type, organic plastics, and so forth. They are all transparent for the eigen luminescence, with a spectral composition lying in the region of sensitivity of antimony-cesium photocathodes used in electronic multipliers.

Inorganic crystals record gamma radiation more efficiently than organic crystals of the same size. This is due to the face that inorganic luminophores are denser and the probability of the same linear dimensions absorbing gamma quanta is greater than in organic crystals. But it is considerably more difficult to make inorganic crystals of large size.

A major shortcoming of luminophores of the "sodium-iodine" type is the fact that they soon become dim when exposed to moisture. To prevent this happening the luminophore is enclosed in a metal casing which strongly absorbe beta radiation and is opaque to alpha particles and protons.

Photomultipliers suffer from relatively high natural noise currents. Hence when nuclear fluxes of small intensity are measured, the number of noise signals may be commensurate with the pulses created by the ionizing particles. But the amplitude of the noise pulse is tens of times smaller than that of the working pulse. This fact enables us to build a recording circuit in which the noise pulses are cut off (descriminated against) from the principal working pulses.

Among the defects of scintillation counters are the following:

a) the need for a stable high voltage supply to power the photo-multiplier;

b) ageing of the photocathodes and "fatigue" of the emitters which show up in loss of sensitivity when the multiplier is used for a long time;

the sensitivity is very soon reduced when the intensity of the luminous and, therefore, radioactive radiation is high;

c) a large spread in the parameters of different photomultipliers, making it difficult to mass produce the scintillation counters.

Despite these shortcomings, the high efficiency and high resolving power of scintillation counters suggest that they will continue to be widely used both in the laboratory as well as in the field dosimetric work as the photomultipliers are gradually improved.

<u>Neutron dosimetry method.</u> Ionization chambers, gas discharge counters, scintillation counters, photographic emulsions and also chemical indicators can all be used to record neutrons.

At the present time boron ionization chambers and proportional counters are commonly used to measure slow neutron fluxes. In the counter (chamber) for the neutrons the gas containing boron (usually borontrifluoride BF_3) is added to the ordinary gas filling the working volume, or else a thin coating of boron is applied to the inside surface of the counter.

The slow neutrons react with the isotope $_5B^{10}$ in the following way

$$_5B^{10} + _0n^1 \rightarrow _3Li^7 + _2He^4,$$

The $_3Li^7$ and $_2He^4$ nuclei formed possess a total kinetic energy of about 2.5 Mev, that is to say they are fast, strongly ionized particles which easily record. The counting rate of these counters (chambers) is proportional to the slow neutron flux. If the counter is fairly large in size, the recording efficiency may attain 10 or more percent. Counters and ionization chambers filled with gases containing hydrogen atoms are used to record fast and intermediate neutrons. In this case the recording is based on ionization produced by the recoil protons. Hydrogen or methane are usually used for this purpose. The efficiency in recording neutrons with these counters is low - only about a tenth of a percent - this being due to the low effective scatter cross-section.

Fast neutrons can also be recorded with a scintillation counter if materials containing hydrogen (stilbene, anthracene and organic plastics) are used

-221-

as the luminophores. A high recording efficiency for neutrons can be comparatively simply attained by means of scintillation counters. In certain cases fast and intermediate neutrons can be recorded by means of slow-neutron counters (chambers). In this case the counter is encased in a fairly large moderator (water or paraffin) which moderates the fast neutrons down to thermal energies. The recording efficiency of these counters is much higher than those based on the recording of recoil protons.

Apart from these methods, radioactive indicators are now widely used for recording neutrons. This method is based on the measurement of a neutron flux from the extent of the radioactivity of an isotope which occurs through its capture by a neutron nuclei.

Table 19 gives some of the radioactive indicators used to record slow neutrons. These indicators are based on radiative capture of slow neutrons with formation of radioactive nucleus.

Table 19

Some radioactive indicators using slow neutrons.

Initial isotope	Type of radioactivity	Half life	Remarks
Mn^{55}	β, γ	2,6 hrs	Used in the form of an acqueous solution of Mn
Au^{198}	β, γ	2,69 days	Used in the form of foil
Na^{23}	β, γ	15 hrs	Used in the form of chemical compound of Na

Table 20 shows radioactive indicators used to record fast neutrons. These indicators are based on the capture of fast neutrons with subsequent emission of a proton. All the indicators of this type are threshhold ones, that is to say they record fast neutrons beginning from a certain energy known as the threshhold energy.

Table 20

Some radioactive indicators for fast neutrons

Initial isotope	Energy threshold	Radioactive isotope	Type of radioactivity	Half life	Comment
Mg^{24}	2.1	Na^{24}	β, γ	14.8 hr	Metal
P^{31}	1.1	Si^{31}	β	170 min	$(NH_4)H_2PO_4$
S^{32}	1.0	P^{32}	β	14.3 days	Flowers of sulfur

Radioactive indicators are convenient in that their dimensions are small and, they are insensitive to gamma radiation and their use in recording neutrons does not involve an electric circuit, as distinct from chambers and counters. But radioactive indicators do not make it possible to carry out continuous measurement since they have to be removed and tested after every measurement. Furthermore, it has to be kept in mind that good accuracy in measuring the neutron flux by means of these indicators can only be attained if the distribution of the recorded neutrons with respect to energy is known. This is because the number of radioactive nuclei occurring in the indicator is not only a function of the neutron flux, but also σ_{cap}, which in the case of most indicators varies over a wide range as a function of the neutron energy.

PENETRATING RADIATION FROM A NUCLEAR EXPLOSION

Penetrating radiation is a particular destructive factor characteristic of nuclear explosions. It consists of a stream of gamma rays and neutrons emitted during the explosion of atomic and thermonuclear explosions. Both the components of the penetrating radiation have their own specific features, hence it is best to consider them separately.

1. Gamma radiation

Gamma radiation sources. Gamma radiation contained in penetrating radiation is produced directly at the moment of explosion during the chain nuclear reaction as well as after the explosion through radioactive decay of the fission products and radiative capture of the neutrons by the atomic nuclei of a variety of elements. Thus, gamma radiation from the nuclear explosion can be divided into the following groups according to its origin:

a) the gamma radiation emitted by uranium or plutonium nuclei at the moment of their fission. This radiation is conventionally called _instantaneous_ radiation.

b) gamma radiation from fission fragments (_fragmentary_ gamma radiation).

c) gamma radiation occurring during the capture of neutrons (_capture_ gamma radiation).

At the moment of fission the nuclei of the uranium or plutonium atoms emit several quanta of different energy. According to measurements, the total energy of the gamma quanta of this instantaneous radiation averages a total of 6 Mev per split nucleus.

Instantaneous gamma radiation is given off during nuclear chain reactions as well as during a certain period following until the material of the bomb flies apart. The effect of instantaneous radiation lasts about 10 microseconds. On account of the brief incandescent period, the part played by instantaneous gamma radiation in forming the dose in small. Furthermore, considerable parts of this

radiation is absorbed by the material of the bomb.

The bulk of the fragment radiation is emitted after the bomb has blown apart and continues until the fission products are carried aloft by the incandescent air. The intensity of the fragment radiation drops rapidly through decomposition of the short-life isotopes (fragments with a short half-life). If the intensity of this radiation is taken as 100% one second after the explosion, at the end of 10 seconds it has dropped to 15% through reduction in the activity of the radioactive fragments and products of their decay. A great effect on reduction of intensity of the fragment radiation near the ground is exerted by the ascent of the atomic cloud. In the first 10 seconds the cloud rises to a height of 500 - 1500 m, according to the power of the explosion. This leads to a marked increase in the distance between the radiation source and the ground. The gamma radiation is considerably weakened by its passage through the layers of air. As a result of the rapid decay of the fission fragments and the rise of the atomic cloud, the effect of fragment gamma radiation on objects on the ground lasts only a comparatively short time (10 - 15 seconds).

The dose of fragment radiation is hundreds of times greater than the dose created at the same distance by the instantaneous gamma radiation.

The radioactive fission products emit gamma quanta of varying energy. It has been reported in the press, for example, that gamma quanta with an energy of about 2.2 Mev are emitted by radioactive fragments with a half-life of 0.5 sec; furthermore, gamma radiation with slightly lower energy has been discovered; it is associated with the fragments with a half-life of about 2 sec. The mean energy of the fragment quanta emitted during the first few seconds following the explosion can be taken as 2 Mev.

During the first 10 seconds after the explosion, the fission fragments emit gamma radiation with a total energy of 1.8 Mev per split nucleus (that is to say per pair of fragments).

The source of capture gamma radiation is the reaction involving the radiative capture of neutrons by atoms from the charge and structural elements of the bomb or shell, as well as chemical elements from the medium through which the neutrons spread after the explosion (air, soil, water, and so forth).

Let us see which radiative capture reactions occur in air when the neutrons from an atomic explosion spread through it. As is known, air consists mainly of nitrogen and oxygen. Oxygen hardly absorbs neutrons at all, even thermal ones. The capture of thermal neutrons by nitrogen nuclei is more successful and the following two nuclear reactions occur at the same time

$$_7N^{14} + _0n^1 \rightarrow _6C^{14} + _1H^1;$$
$$_7N^{14} + _0n^1 \rightarrow _7N^{15} + \gamma.$$
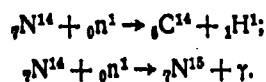
In the first case the result is a proton and the nucleus of the radioactive carbon isotope. Carbon 14 is a beta-active material. As it slowly decays (half-life $\underline{T}$ = 5570 years), it emits beta particles with energy up to 0.15 Mev. The effective section of the reaction σ = 1.7 barns.

In the second case the result is the nucleus of an atom of a nonradioactive (stable) nitrogen isotope and capture gamma radiation. For this reaction σ = 0.1 barns. The probability of a reaction accompanied by the formation of a proton is considerably greater than the radiative capture reaction. Nevertheless, the proportion of capture radiation in the total dose of penetrating radiation may be considerable since a huge number of neutrons are formed during the explosion.

In most materials the spectrum for the capture radiation , that is to say the energy distribution of the gamma quanta, is very complicated. The predominance of fired gamma radiation is characteristic of it.

In particular, about 35 quanta with energy ranging from 3 to 5 Mev, 90 quanta ranging between 5 and 7 Mev and 39 quanta with more than 7 Mev are emitted by nitrogen nuclei for every hundred radiative captures. There is no reliable data on the existence of gamma radiation with energy less than 3 Mev. It is

assumed however, that the proportion of this radiation is small. The total energy of the quanta emitted during each capture process is 10.8 Mev.

A large part of the energy of capture radiation is transferred by the quanta averaging 6 Mev.

Calculations show that in the event of absorption of all the neutrons by the nitrogen in the air, the gamma radiation emitted is 1.0 - 1.3 Mev per each split nucleus in the atomic charge.

The period of action of the capture radiation is determined by the lifetime of the neutrons, which is several fractions of a second in air. Intensity of the capture radiation depends on the amount of nitrogen in the air (air density) the number of released neutrons (power of the explosion), the structural features of the atomic bomb and certain other features.

The majority of capture gamma quanta has greater energy than the fragment quanta, hence they are more penetrating. As the distance from the center of the explosion increases, there is a peculiar kind of filtration - the softer fragment radiation is absorbed earlier and the proportion of it drops more and more. At some distance away the fragment radiation is absorbed to such a degree that it is virtually only the capture gamma radiation which has any effect.

Gamma radiation dose. The gamma radiation dose from penetrating radiation depends on the caliber of the bomb and the altitude of the explosion, and declines rapidly with distance as a result of two simultaneous effects: the square of the distance and the absorption of the radiation by air. The greater the distance, the greater the surface area through which the gamma rays pass. If the distance is doubled, the surface is quadrupled and the gamma ray flux is quartered, that is to say the number of quanta passing through the unit of surface. Hence the dose varies in inverse proportion to the square of the distance. The decrease in the dose through absorption and scatter of gamma quanta by the air is exponential.

Fig. 70 shows the gamma radiation dose at different distances from the

-227-

center of an aerial explosion for bombs with a TNT equivalent of 2,000, 20,000 and 200,000 tons.
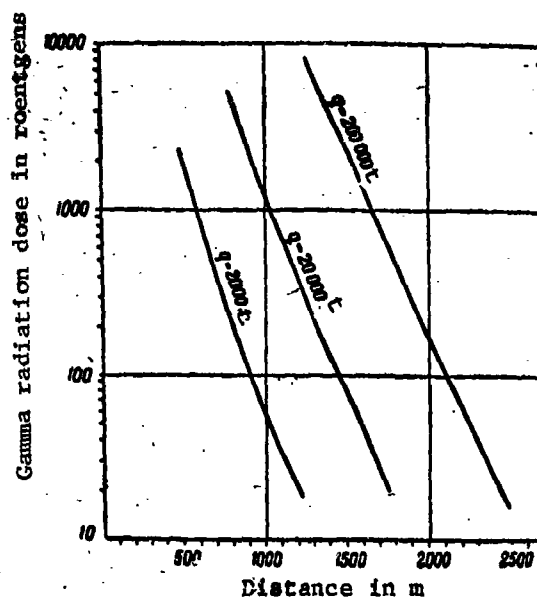
Fig. 70. Gamma radiation dose as function of distance from center of explosion.

In an aerial explosion the distance is usually measured from the epicenter, so in order to calculate the dose the distance from the center of the explosion has to be worked out with consideration for the height of the explosion. If we designate the distance from the epicenter R_e, and the height of the explosion H, the distance between the center of the explosion and any point on the ground is determined by the equation

$$R = \sqrt{H^2 + R_e^2}.$$

It is easy to see that at $R_e = 0$, that is to say right at the epicenter, the distance from the center of the explosion is equal to the height of the explosion.

The radiation dose from the explosion of the same atomic minitions increases with the distance from the center of the explosion. But the distance of a given point on the ground depends on the height of the explosion. This relationship is particularly marked a short way from the point of explosion and is clearly

-228-

berne out by the following numerical examples.

An object located 100 m from the center of a ground level explosion ($\underline{H}$ = 0) is 610 m from the center of an aerial explosion at $\underline{H}$ = 600 m. If the object is moved 2000 m from the center of the ground level explosion, keeping the conditions of the explosion, the distance from the center of an aerial explosion becomes 2080 m. Thus, the dose of gamma radiation at short distances from the center of a ground level explosion is much greater than at the distances reckoned from the epicenter of an aerial explosion. At large distances, however, where the height of the explosion virtually has no effect on the distance, the gamma radiation dose for both types of explosions is approximately the same. That is why the radius of the area in which there may be cases of medium-degree of radiation sickness from an aerial explosion (a dose of 200 - 300 roentgens)differs comparatively little from the radius of the area of cases after a groundlevel explosion.

It should be pointed out that on account of the strong absorption of the radiation by the air, even a slight increase in distance produces a considerable reduction in the radiation dose. For example, if the distance is increased from 1 to $1\frac{1}{2}$ kilometers, that is to say by a factor of 1.5, the dose is reduced by a factor of more than 15.

Naturally, if the caliber of the bomb is changed, the total amount of gamma quanta emitted during the explosion of it is also changed. Variation of the caliber involves variation in the number of split nuclei, that is to say the number of fission fragments - the principal sources of gamma radiation.

It can be assumed that the total amount of gamma quanta is proportional to the number of split atomic nuclei, and therefore to the amount of energy emitted during the explosion. The dose of gamma radiation created at different distances from the site of the explosion is also approximately proportional to this quantity. Thus , for a rough evaluation of the dose from atomic munitions which do not differ too extensively in their TNT equivalent we can use the following simple

equation

$$D_1 \propto D_2 \frac{q_1}{q_2},$$

where D_1 is the dose from an atomic bomb with a TNT equivalent q ;

D_2 is the dose from an atomic bomb with the TNT equivalent q . ....

For example, it is known that at 1500 m from the center of an explosion, given q_2 = 20 kilotons, D_2 = 80 roentgens (see graph in Fig. 70). The dose from an atomic bomb with a 10 kiloton caliber at the same distance is approximately 40 roentgens.

It was noticed, however, that when the power of the explosion was increased, the gamma radiation dose did not increase in proportion to the TNT equivalent, but much more rapidly. For example, 1600 m from the point of the explosion of an atomic charge with a TNT equivalent of 1000 tons the gamma radiation dose was 2.5 roentgens; when the explosion was equivalent to a 100,000 tons, the dose was stepped up by a factor of 150 at the same distance, and amounted to 375 roentgens. This relationship between the dose and the distance is due to the effect of the shockwave moving away from the point of explosion while the gamma rays are spreading.

It was established by theory and proved by experiment that the absorption of gamma rays over the journey from the center of the explosion to the point under consideration was a function of the redistribution of the air masses, which is caused by the passing shockwave.

As we know, when a comparatively strong shockwave passes by (when the pressure at the front is considerably greater than atmospheric), the bulk of the air pulled along is concentrated in a thin layer near the wave front. Inside the wave there is formed a region of low air density - a cavity. This low-density region also lasts for a short time after the passage of the shockwave, when the original pressure is restored. This is because when the wave passes by, the air is heated up. It is usually heated up to a particularly high temperature at a short distance from the center of the explosion. The higher the temperature of

-230-

the hot air, the less its density and therefore the better the gamma rays pass through it. It takes a fairly long time for the air to cool down again and return to normal density, in fact much longer than the emission time of most of the gamma radiation. For example, 5.35 seconds after the shockwave has passed ($q = 300,000$ tons) the radius of the cavity in which the density is 5 times smaller than in the surrounding air, is 600 m.

It has already been mentioned that the intensity of the gamma radiation at a given point on the ground decreases through decay of the fragments and ascent of the atomic cloud. The formation of a cavity of greatly rarefied air brings about an increase in the gamma radiation intensity, since the rays are virtually unabsorbed when they pass through it. The rise in intensity is marked mostly whenever the shockwave compression zone passes the point where the dose is being measured. In the given case this point is inside the cavity, and there is no absorption of the gamma rays. But the presence of the shockwave reduces the absorption and therefore leads to an increase in the dose as well at the point at which the shockwave front has not yet reached.

An equation on the following type is put forward for calculating the gamma radiation dose from an atomic explosion

$$D = \frac{A}{R^2} \, e^{-\frac{R}{\lambda_{eff}}}$$

where A is the multiplier taking into account the power of the explosion and the effect of the shockwave;

R is the distance from the center of the explosion;

λ_{eff} is the effective path of the gamma quanta in air. depends on the density of the medium and is determined experimentally.

This equation can be expressed in logarithmic form in the following way

$$\lg (D \cdot R^2) = \lg A - \frac{R}{\lambda_{eff}} \cdot 0.434.$$

-231-

Fig. 71 shows a typical relationship between dose and distance. The distance from the center of the explosion is plotted along the x-axis and the logarithm of the product of the dose and the square of the distance is shown along the y-axis.

This graph, which is plotted from experimental data, can be used to find A and λ_{eff}.

The graph in Fig. 71 clearly shows the existence of three regions in which the dose varies with distance. Points on the earth's surface at a distance $R < R_1$ from the center of the explosion, that is to say in region I, fall in the shockwave cavity throughout the period of action of the gamma radiation. In this region the dose varies in inverse proportion to the square of the distance and the logarithm of the product DR is therefore constant. In region II ($R_1 < R < R_2$) fragment radiation is predominant, and in region III ($R > R_2$) capture radiation is prevalent. The distances R_1 and R_2 are the boundaries of these regions.
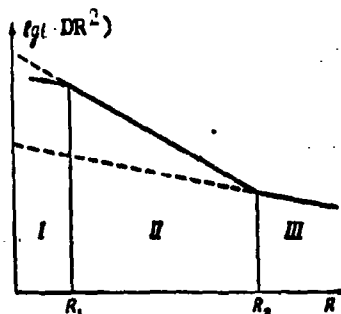
Fig. 71. General view of relationship between gamma radiation dose and distance.

The most characteristic region for an assessment of the damaging effect of gamma radiation is region II, since at distances R_2 or more the dose does not usually exceed 100 roentgens. R_1 and R_2 are shown in Table 21 as functions of the power of the explosion.

The dose of fragment gamma radiation (in region II) for an aerial explosion can be calculated from the equation

$$D = 1.4 \cdot 10^9 q \left(1 + 0.2 q^{0.63}\right) \frac{e^{-\frac{R_7}{300}}}{R^2},$$

-232-

Table 21
R₁ and R₂ for nuclear charges with different TNT equivalents

q, 1000 t	2	20	200	2000
R_1, m	250	400	1200	2000
R_2, m	1100	1400	2400	3500

where q is the TNT equivalent of the atomic charge in thousands of tons;

R is the distance from the center of the explosion in m;

ρ is the density of the air in kg/m³.

This equation can be reduced to the form of the one given earlier if we take it that

$$A = 1.4 \cdot 10^9 q (1 + 0.2 q^{0.65}) \ \& \ \lambda_{eff} = \frac{300}{\rho}.$$

In air of normal density (temperature 28°C and pressure 760 mm Hg) $\lambda_{eff} = 250$ m.

The multiplier represented as a sum in inside parenthesis is designated K_D ($K_D = 1 + 0.2 \ q^{0.65}$). This multiplier takes into account the effect of the shockwave on the propagation of gamma rays through air and is often called the cavity factor. If $K_D = 1$, the dose is proportional to the power of the explosion. But $K_D \cong 1$ only for small TNT equivalents.

The gamma radiation dose is greater at the same distances from the center of the explosion in a groundlevel explosion than in an aerial explosion of the same power. This is because in region II (Fig. 71) the shockwave from a ground-level explosion is stronger and the effect of its cavity on the dose is therefore also much stronger. An approximate calculation of the dose for a groundlevel atomic explosion can be made from the equation

$$D = 2.8 \cdot 10^9 q (1 + 0.3 q^{0.65}) \frac{e^{-\frac{R\rho}{300}}}{R^2}.$$

The capture gamma radiation only lasts for 0.2 - 0.3 seconds, hence the shockwave hardly affects its propagation at all.

These equations for calculating the gamma radiation dose relate to bombs based on the fission of heavy nuclei. The relationship between the explosion energy (TNT equivalent) and number of quanta emitted and neutrons emitted is different for thermonuclear explosions, since some of the energy is released through synthesis.

As has already been mentioned, the gamma radiation dose is made up of the dose of fragment radiation accumulated over a period of several seconds, and the *DOSE* of capture radiation, the effect of which is for practical purposes complete 0.3 seconds after the explosion.

The time taken for the dose to accumulate depends on the distance and the energy of the explosion. The greater the distance, the more rapidly the dose accumulates, since the role of capture radiation is increased with distance.

The time over which the cavity created by the shockwave acts increases with the TNT equivalent of the explosion, and the time during which the gamma radiation dose is accumulated is increased accordingly, or in other words, there is a slower accumulation of the dose. Let us quote an example to substantiate what has been said. During the explosion of a charge q = 200,000 tons, at a distance of 1500 m, 30% of the total dose is accumulated during the first second whereas when q = 2000 tons and the distance is the same, up to as much as 80% of the dose is accumulated during this period. Fig. 72 shows a graph for the accumulation rate of the gamma radiation dose for an intermediate caliber atomic bomb. The data given in the graph, according to foreign literature, corresponds to the distance over which a dose of 400 roentgens should be obtained.

The relationship between the gamma radiation dose and the power of the explosion is shown in Fig. 73. Using the graphs in this figure we can determine the distance from the center of the explosion where the given dose of gamma radiation can be expected, if we know the power of the explosion in terms of kilotons of TNT equivalent. Each graph shows a certain dose, to wit: 30, 100, 300 and 1000 roentgens. These graphs can be used to prove that during the explosion of

-234-

an atomic bomb with a TNT equivalent of 20 kilotons, a dose of 30 roentgens is obtained at the distance of 1750 m, and that the same dose is obtained at 1400 and 2300 m when the caliber is 5000 and 100,000 tons.

At the present time the foreign press contains reports to the effect that anti-aircraft and aviation jet missiles can be fitted with atomic charges intended to destroy targets in the air.

When the explosion occurs at a high altitude, the emitted gamma rays and neutrons are propagated through rarefied atmosphere and, consequently, are weakened along their journey from the point of explosion to a lesser extent.

Let us see how the destructive range of penetrating radiation varies for an aerial explosion, compared with an explosion near the ground. For the sake of convenience and greater lucidity we will consider that if the atomic explosion has occurred at a certain height H, the object destroyed is also at this height. For example, at a height of 10 km it is reduced by a factor of 3, at a height of 20 km by a factor of 14, hence the variation in attenuation of the penetrating radiation with height is very considerable.

The effective distance for the absorption of gamma radiation increases with a decrease in the air density[1)]

$$\lambda_H = \lambda_0 \frac{\rho_0}{\rho_H},$$

where λ_0 is the effective distance of the absorption of radiation in air with a density of ρ_0 (normal near the earth);

λ_H is the effective path of the gamma quanta in air with density ρ_H (at a height H).

Table 22 below gives the effective distances λ_{eff} calculated for different altitudes. It is assumed here that the atmospheric conditions by the earth are such that $\lambda_{eff} = 250$ m.

Thus, as the altitude of the explosion is increased from 0 to 20 km, the thickness of the air layer weakening the gamma radiation 2.7 times is increased by almost a factor of 14.
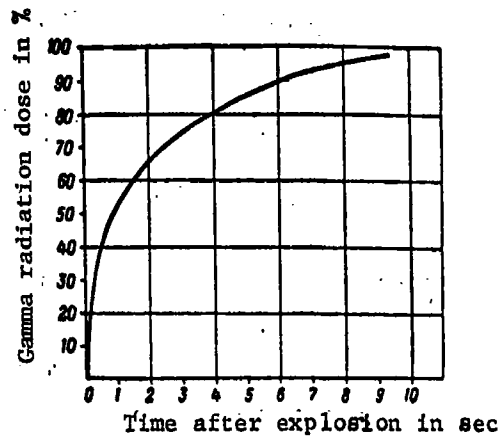
-235-

Fig. 72. Accumulation rate of the gamma radiation dose for
an intermediate caliber atomic bomb
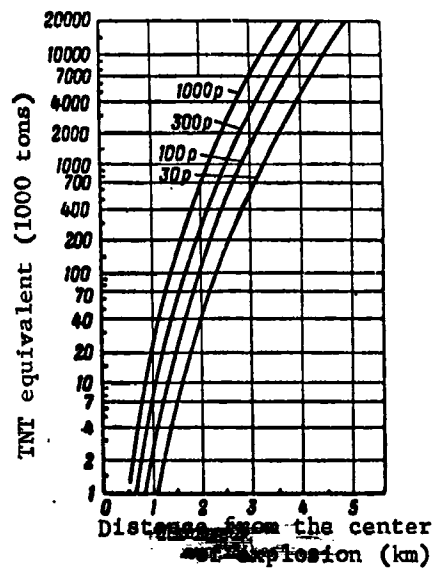
Fig. 73 Gamma radiation dose as a function of TNT equivalent
and distance from the center of the nuclear explosion

-236-

Table 22

Effective path of gamma quanta.

Height of explosion	0	5	10	15	20
λ_{eff} (m)	250	420	740	1600	3400

By applying this equation we can determine how the destructive range of the gamma radiation varies during an explosion at a set height. Calculations show that the dose which can be obtained in a groundlevel explosion at 1 km is created at approximtely 2 km when the height of theexplosion is 10 km and at 4 km when the height of the explosion is 20 km.

2. Neutron radiation.

The neutrons formed during an atomic explosion are subdivided into instantaneous and delayed neutrons. The instantaneous fission of neutrons have energies, beginning with thermal energy (0.025 ev) and ranging approximately to 14 Mev, the mean energy being about 2 Mev.

The release of instantaneous neutrons occurs during the fission of nuclei and therefore takes only a few millionths of a second. As they pass through the material of the bomb, particularly the casing, the neutrons interact with the atomic nuclei and experience delay or capture.

It can be considered that the neutrons are not absorbed for practical purposes by the bomb casing; the casing flies apart without having time to capture them. Consequently, almost all the free neutrons, that is to say those not taking part in the chain fission reaction, emerge into surrounding space. Nevertheless a large quantity of these neutrons are greatly slowed down by the bomb material.

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[1]

For purposes of convenience in the equations given below the subscript "eff" is not used.

Neutrons moderated to thermal energy are distributed near the center of the explosion, forming a peculiar kind of "neutron cloud".

A comparatively small number of free neutrons pass through the bomb casing without being moderated. Like the gamma rays, these neutrons spread in all directions from the point of explosion.

Delayed neutrons are emitted by some of the fission fragments during the few seconds or so following the explosion, and are not therefore moderated by the bomb material. In the fission of atomic nuclei of uranium 235 by thermal neutrons, 0.73% of the total number of neutrons obtained are delayed neutrons; during the fission of plutonium 239 the number of delayed neutrons is slightly less - 0.36%. Their energy is approximately 0.4 - 0.6 Mev. It has been shown by means of rapid chemical analysis of the fission products that the source of the delayed neutrons is a bromine isotope with a half-life of 55.6 seconds, and iodine isotope with a half-life of 22 seconds, and certain other short-lived fission fragments. Despite the fact that the proportion of delayed neutrons is small, their effect on the neutron radiation dose may be rather large. This is because they are not weakened by the bomb material. The neutron radiation is effective for a few tenths of a second.

The neutron flux is the characteristic used for a quantitative assessment of the neutron radiation from a nuclear explosion. The neutron flux is the total number of neutrons which pass through 1 cm of surface throughout the period of radiation. By knowing the neutron flux we can calculate the dose.

To calculate the fast neutron dose as a function of distance, we use equations similar in structure to those for calculating the gamma radiation dose.

The proportion of neutrons in the overall dose of penetrating radiation is slightly increased by a reduction in the caliber of the atomic weapon. Furthermore, the neutron yield during an atomic explosion and the neutron dose, as distinct from the gamma radiation dose, depend on the design of the bomb and the fissionable material. This is clearly illustrated by the graphs in Fig. 74.

The bomb exploded over Hiroshima contained uranium 235 as the nuclear explosive.
The atomic charge in the bomb dropped on Nagasaki was made of plutonium. These
bombs were quite different in design. Measurements have shown that in Hiroshima
there were approximately 10 times more slow neutrons than in Nagasaki; there were
approximately 3 times as many neutrons with energy greater than 2.5 Mev.
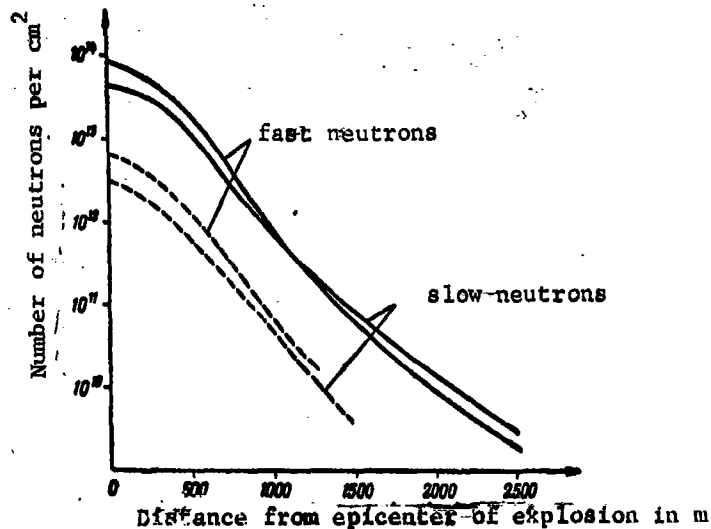
Fig. 74. Variation in neutron flux with distance (solid curves show
Hiroshima explosion, dotted curves show the Nagasaki explosion)

The damaging effect is mainly due to neutrons with energies from 0.2
to 0.3 Mev; the effect of slower neutrons mainly shows up in the formation of
artificial radioactive substances.

The total dose of penetrating radiation is determined by the sum of the
gamma radiation dose in roentgens and the neutron dose expressed in biological
roentgens equivalents. The dose created by neutrons over the same distance from
the center of the atomic explosion is less than the gamma radiation dose, which is
more than half the total dose of penetrating radiation. Hence calculation of the
protective layer for penetrating radiation may be made in many cases from the
gamma radiation alone.

3. Penetrating radiation during a thermonuclear explosion

Hydrogen isotopes compounded with lithium, particularly lithium deuteride

-239-

are used as thermonuclear explosive, as has already been mentioned. The neutrons from the atomic charge used for a thermonuclear bomb explosion form tritium when they react with the nuclei of the lithium isotope

$$_3Li^6 + _0n^1 \rightarrow _1T^3 + _2He^4.$$
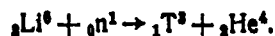
A number of complex nuclear reactions between the deuterium, tritium and lithium release a large quantity of energy, some of which is carried away by the neutrons formed. Other reactions may also occur during a thermonuclear explosion.

The products of these reactions are mainly alpha particles and neutrons; there is one alpha particle and one neutron for each pair of combining deuterium and tritium nuclei. During the explosion of 1 kg of a mixture of deuterium and tritium the number of neutrons released is $1.2 \cdot 10^{26}$. The explosion of 1 kg of uranium produces considerably fewer neutrons. It is known that during the fission of every uranium nucleus an average of 2.5 neutrons are released. If we assume that 1 neutron is spent on sustaining the chain reaction, while the remainder do not take part, the number of the latter is $3.8 \cdot 10^{24}$, that is to say 30 times fewer than in the first case.

The penetrating radiation from a thermonuclear explosion is determined by the flux of both neutrons and gamma rays, which occur as a result of interaction between neutrons and the elements contained in the bomb material and the air.

The destructive range of penetrating radiation is less than the distances over which destruction by the shockwave and luminous radiation are possible. This can be confirmed by means of a rough calculation.

Let us assume (quite arbitrarily) that atomic nuclei contained in 12 kg of tritium mixed with deuterium take part in the combination of these two isotopes. In this case the reaction produces approximately $1.4 \cdot 10^{27}$ neutrons. Let us further assume that all the neutrons pass through the bomb casing without loss, taking it that the nuclear reaction occurred inside the bomb, and that they fly asunder in

surrounding space. Calculations show that 5 km from the site of the explosion of the given charge the neutron flux will be $1.7 \cdot 10^9$ neutron/cm^2. If it is considered that these neutrons have energy of at least 3 Mev, a dose of 1 bre is produced by neutron flux of $1.4 \cdot 10^7$ neutron/cm^2. Thus, the neutron dose is equal to 120 bre. It has been found that when the whole of the body is irradiated with a dose of 100 - 200 bre, there may be slight injury, but not endangering human life. Thus, a destructive range of penetrating radiation with respect to persons who have not taken shelter is about 5 km. In actual fact this distance should be much less since the neutron flux is weakened by the casing and other design elements in the bomb, and there is also considerable weakening of the flux in the air. In the so-called hydrogen-uranium bomb, the greater part of the explosion energy is released through fission of atomic nuclei in the uranium casing. Here, just as in the atomic bomb, we find the formation of fission fragments, instantaneous gamma radiation and neutrons. Hence, when determining the dose of penetrating radiation, the hydrogen-uranium bomb can be considered an atomic bomb, and the same methods as was set forth above can be applied.

4. Calculation of thickness of defenses

<u>Weakening of gamma radiation dose.</u> Calculation of the weakening effect on gamma radiation doses made by different forms of protection can be made from the equations given in Chapter IV. But an exact calculation on the basis of these equations is fraught with great difficulties. This is due to the fact that the gamma quanta emitted by the fission fragments show a great variety of energies. While passing through the air to a given point on the earth's surface, they interact with the atoms of the air. Hence the energy spectrum for gamma radiation arriving at the surface of a protective obstacle becomes still more complex and the theoretical determination of the attenuation and accumulation factors, which depend on the quanta energy, proves extremely difficult.

Calculation of the degree of weakening of the gamma radiation dose by any obstacle can be made with fair accuracy on the basis of experimental data from

nuclear tests. During these tests the thickness of the half-weakening layer $\underline{d}$ is determined for a wide beam of gamma rays, and then there is no need to make corrections for scatter. In this case the equation for the weakening of the gamma radiation dose acquires the following form

$$D = D_0 2^{-h/d},$$

from which the degree of weakening is equal to

$$K = \frac{D_0}{D} = 2^{h/d},$$

where D_0 is the dose in front of the protective obstacle, the thickness of which

is $\underline{h}$;

D is the dose behind the obstacle.

It is known that for soil $\underline{d} = 14$ cm, for lead 1.8 cm, for concrete 10 cm and for steel 2.8 cm, and so on.

Fig. 75 gives the thickness of different materials needed to reduce the gamma radiation dose by a factor of 2, 4, 8 and 16.

It can be roughly considered that in substances which have approximately the same mean atomic number the attenuation factor is directly proportional to the density of the substance and is a function of the gamma quantum energy. For the gamma quantum of the given energy the attenuation factor is only a function of density of the substance. In this case equal amounts by weight of different materials are required for the same degree of weakening.

Table 23 shows the density of certain materials used for protection against penetrating radiation.

The density of wood and earth may vary by a factor of $1\frac{1}{2}$ or 2 in accordance with the moisture content and composition, hence their ability to weaken the gamma radiation may also vary.

Let us find the half-weakening layer, let us say, for wood, knowing that it is 14 cm for soil. The mean density of wood is 0.9 g/cm^3, and of soil 1.6 g/cm^3. The half-weakening layer of wood will be as many times greater as that of soil as the density of wood is smaller than the density of soil.

-242-
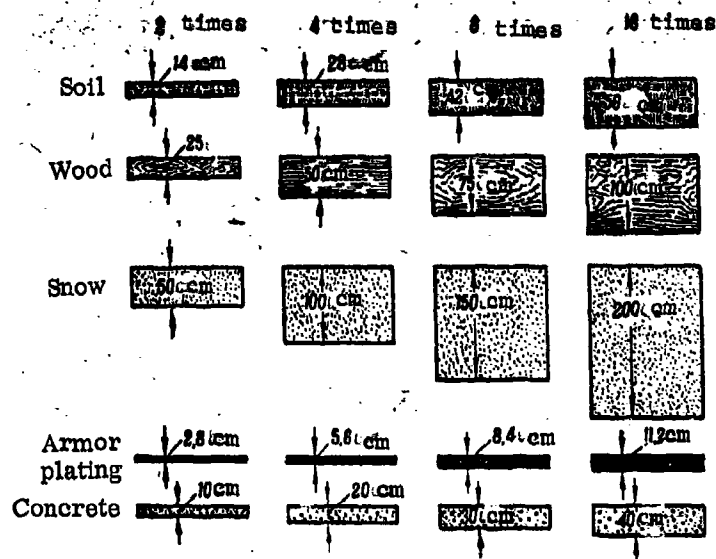
Fig. 75. Weakening of gamma radiation in penetrating radiation by different materials.

Table 23

Density of some materials used in defense constructions

Material	Density in gr/cm^2
Lead...	11.3
Water...	1.0
Steel...	7.6 - 7.9
Aluminum...	2.7
Wood:	
dry birch	0.5 - 0.8
damp birch	^.8 - 1.1
Concrete...	1.8 - 2.5
Ordinary brick..................................	1.4 - 1.6
Earth...	1.3 - 2.0

Hence the solution takes the very simple form

$$d = \frac{1,6 \cdot 14}{0,9} = 25 \quad cm$$

In the same way we can find the half-weakening layer for any materials.

Let us now set ourselves another problem. How can we determine the thickness of the layer of given material needed to reduce the gamma radiation several times?

Let us assume, for instance, that we are required to determine the thickness of the soil covering a trench in order to reduce the dose by a factor of 50.

To solve the problem we use the equation we have already met before

$$K = 2^{h/d}.$$

In this example, $\underline{K} = 50$, $\underline{d} = 14$ cm and we are to find $\underline{h}$.

The problem can be solved by means of logarithms

$$\lg K = \frac{h}{d} \lg 2,$$

from which

$$h = d \frac{\lg K}{\lg 2}.$$
$$\lg 50 = 1,7;$$
$$\lg 2 = 0,3;$$
$$h = 14 \frac{1,7}{0,3} = 80 \quad cm$$

A slightly different problem can also be set. We are required to check whether a ready-made installation will weaken the penetrating radiation.

Let us assume that we have a cellar with a roof 0.8 m thick. By what factor does this layer of concrete reduce the radiation dose?

In this problem $\underline{h} = 80$ cm, $\underline{d} = 10$ cm and we are to find $\underline{K}$.

Solution. Let us find the number of half-weakening layers in the layer 0.8 m thick

$$\frac{h}{d} = \frac{80}{10} = 8.$$

Now let us determine the degree of weakening

$$K = 2^8 = 256.$$

Thus, a layer of concrete 80 cm thick reduces the gamma radiation dose by a factor of 256.

When making these calculations we have assumed throughout the same values of the half-weakening layer as has been found for the most favorable circumstances. In other words, we have taken it that the gamma rays reaching the ground at different distances from the point of explosion, possess roughly the same energy. In actual fact this is not the case. The energy spectrum of gamma radiation varies with the distance from the point of explosion. The gamma radiation spectrum also varies when it passes through a protective obstacle. If the gamma quantum energy becomes less, the weakening of it by the obstacle is more efficient; a layer of reduced thickness is required to halve the dose.

Thus, in certain cases the halfweakening layer for concrete may be 7 or 8 cm. Hence a concrete wall 50 cm thick brings about a reduction in the gamma radiation dose by a factor of 32, if d = 10 cm, and 75 if d = 8 cm.

In a number of cases, therefore, the calculated degree of weakening is less than what actually occurs, or in other words, the thickness of the protective area includes a greater safety margin.

If the protective barrier consists of several layers of different materials, for example soil and concrete, soil and wood, and so on, the degree of weakening has to be calculated for each layer separately, and the results multiplied together.

Weakening of the neutron flux. The degree to which the neutron flux is weakened when it passes through a medium depends on the energy of the neutrons and the chemical composition of the medium. As is known, the fast neutrons are poorly absorbed by practically all substances, so their velocity of motion has to be reduced at the beginning, after which measures ensuring total absorption can be taken.

A good neutron moderator is water. The delayed neutrons are successfully captured by the hydrogen nuclei. But during the process gamma rays with high energy

-245-

are given off and the layer of water needed to weaken them has to be fairly large. If we add a small quantity of boron to the water, let us say in the form of boric acid, the slow neutrons are mainly absorbed by the boron.

For protection from neutrons and gamma radiation when working with nuclear reactors, use is commonly made of concrete. The concrete contains hydrogen and other comparatively light elements (oxygen, aluminum, silicon and calcium). As they pass through the concrete, the neutrons are moderated and absorbed. Gamma radiation is also weakened extensively by the substances contained in the concrete.

For an approximate calculation of the weakening of a neutron dose we can apply the equation in the form already familiar to us

$$D_H = D_{H0} 2^{-h/d_H},$$

where D_{H0} is the neutron dose in front of the obstacle, the thickness of which is h;

D_H is the neutron dose behind the obstacle;

d_H is the half-weakening layer.

The quantity d_H is a complex function of the neutron energy and is usually determined experimentally.

For neutrons with a mean energy of 2 Mev, the path in water is about 4 cm, while the half-weakening layer is about 3 cm. It is interesting to note that with respect to weakening neutron radiation iron behaves in more or less the same way as water - its half-weakening layer is slightly more than 4 cm.

Tests carried out with neutron fluxes in nuclear reactors show that to weaken the neutron flux by a factor of 2 we need to have 8 - 10 cm of ordinary concrete.

On account of the high penetrating capacity of gamma rays and neutrons, ordinary clothing and personal anti-gas defense measures may not protect humans from their effect.

Protection from penetrating radiation. Natural cover should be used for protection from penetrating radiation, e.g., folds in the terrain and local features, as well as artificial constructions - various fortifications including

-246-

simple trenches.

Covered constructions for protection from the affect of the shockwave usually provide protection from penetrating radiation as well. The gamma rays and neutrons are weakened as they pass through the layer of soil and the ʀᴏᴏғ over the installation, and the greater the thickness and density of the protective layer, the more this is so. In covered slit trenches and ditches, the penetrating radiation is reduced by a factor of 25 - 30. Dugouts and shelters, which afford more reliable shelter for personnel, have a layer of soil above the top of at least 1 m thick. In dugouts the penetrating radiation dose from an atomic explosion is approximately 200 - 300 times smaller than on the ground, and more than 2000 times smaller in the lighter type of airraid shelter.

Open trenches and dugouts reduce the dose of penetrating radiation from an aerial atomic explosion by a factor of 10 - 20. Supposing the dose of gamma radiation is 500 roentgens on the ground, in the top half of a trench it is approximately 200 roentgens, and on the bottom of the trench decreases to 50 roentgens. In this case, both the gamma rays as well as the neutrons are absorbed by the walls of the trench to a great extent. But certain number of gamma quanta and neutrons get into the trench from the top where there is no protection, on account of scatter in the air.

Fig. 76 shows that the penetrating radiation dose in a trench is determined principally by the radiation scattered in the atmosphere.

Scattered radiation also gets inside so-called semi-covered constructions with different types of entry holes. The stream of gamma rays or neutrons finding their way into the shelter through the openings are further scattered on the inside of the wall. This scattered (reflected) radiation may cause damage or injury in certain cases at points which are not directly in the way of the incoming beam of quanta and neutrons.

The dose in a semi-covered construction depends not only on the power of the explosion and the distance away, but also on the position of the opening with
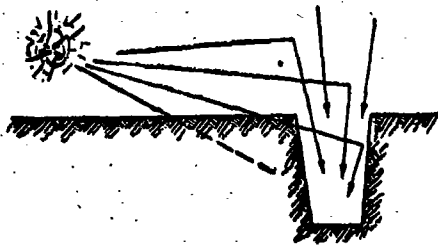
Fig. 76. Diagram showing effect of penetrating radiation on an object in a
trench.

respect to the center of the explosion and also the dimensions of the opening.

Good protection from penetrating radiation is provided by tanks. The armor plating of a medium tank reduces the radiation dose by a factor of 10 - 15. But it should be kept in mind that the armor gives considerably less protection from neutrons than from gamma rays. Furthermore, radioactive isotopes may be formed in the elements making up the armor plating.

5. Destructive effect of penetrating radiation

Radiation thickness. The disturbances caused in the organism by nuclear radiation may lead to a particular form of illness known as radiation sickness. The basis of this disturbance of the physiological processes has not so far been fully discovered. It has been found that the greater the radiation dose received, the more serious the case of radiation sickness. Studies on animals and experience gained in working with x-rays show that the way the dose is received is of extreme importance: whether over a prolonged period or in a short time, whether received by the entire organism or by one particular organ. It seems that a human being can stand a dose of 50 roentgens without aftereffects if irradiated all over the body over a short time and in one go. The tissues in the organism are able to recover by themselves if they are not damaged extensively. Hence within certain limits irradiation in small portions over a long period is less harmful than brief irradiation by the same total dose. For example, 2900 roentgens are required to

cause fatality among guinea pigs, irradiating them each day (for eight hours) with 4.4 roentgens, whereas the same fatality was observed when they were radiated all at once with 300 roentgens.

When a human being is subjected to overall irradiation in doses ranging from 50 to 100 roentgens, we observe the first signs of radiation sickness without incapacitation. Higher doses of radiation may cause radiation sickness. Radiation sickness of VARYING severity may be caused in different people by the same dose, according to the resistance of the organism and the general state of health.

The general regularity governing radiation sickness is an inverse relationship between the period it takes to develop and the dose - the greater the dose, the shorter the period over which the sickness developes.

How does radiation sickness occur?

Immediately after the effect of large doses of radiation, there is usually developed a so-called primary reaction phase, which continues from several seconds to several days and is marked by a feeling of weakness, gastric disturbances and loss of appetite. There is also a change in the composition of the blood. Then comes the so-called latent period or period of apparent recovery. The overall condition of the patient is improved and no outward/ SYMPTOMS or illness are observed. But during this phase of the radiation sickness there is a reduction in the number of leucocytes and thrombocytes in the blood. The latent period (incubation period) lasts from several days to two or three weeks. The greater the radiation dose, the briefer the period. Next comes the third phase of development of the sickness. The patient loses his appetite; the gastric disturbances are aggravated, the hair beings to fall out, there is hemhorrhage and bleeding (in the skin, in the oral cavity, etc.) and the number of leucocytes is sharply reduced. This reduction reduces the capacity of the organism to resist various infections.

This is why the basic complication accompanying radiation sickness is usually an infectuous disease, particarly angina. When the dose is comparatively weak, it is not so much the radiation injury proper which is important, as the

overall reduction in the organisms resistance, which from time to time shows up in casual colds, intestinal troubles and other such ailments.

A clear illustration of the change in the number of leucocytes, erythrocytes and thrombocytes in the blood after irradiation is shown by the curves in Fig. 77.
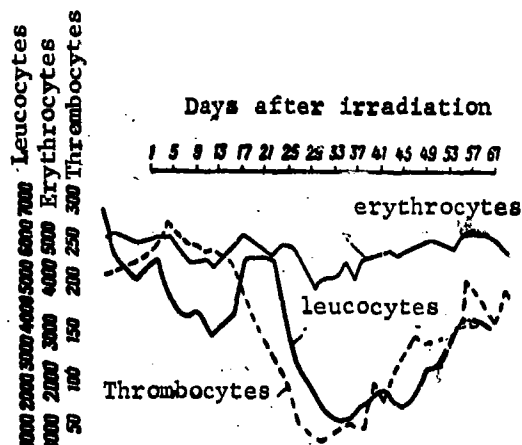
Fig. 77. Variation in the number of leucocytes, erythrocytes and thrombocytes in a human being subjected to a dose of 300 roentgens of gamma radiation: on the left-hand side there are three scales: the figures on the L/scale show the leucocytes in 1 mm ; the Er scale shows the number of thousands of erythrocytes per 1 mm^2, and the Th scale shows the number of thrombocytes in thousands per mm^2.

As has already been pointed out, the reduction in the number of leucocytes (white corpuscles) reduces the organism's ability to resist infection. The deficiency of erythrocytes (red corpuscles) reduces the supply of oxygen to the tissues, and the decreased number of thrombocytes (blood platelets) impairs the clotting of the blood, making bleeding more dangerous.

The third period is then replaced by the fourth, recovery. There is gradual waning of the symptoms, one after the other, in accordance with the physical makeup of the patient.

There are three degrees of radiation sickness: minor cases, medium cases and severe cses.

Minor cases of radiation sickness occur when the total irradiation dose is 100 - 200 roentgens and there are no typical symptoms. The latent period may last from 2 to 3 weeks. Then comes general debility, nausea and

-250-

vertigo, and the number of white corpuscles in the blood is reduced. There is complete recovery after minor cases of radiation sickness.

Radiation doses of 200 to 300 roentgens may cause moderate radiation sickness. Here the infection is marked by the same symptoms as for a minor case, except that they are more marked. Given efficient treatment, there is recovery after one and a half or two months.

Serious cases of radiation sickness develop when the dose is greater than 300 roentgens. It advances rapidly and the latent period is cut down. If treated in good time, the patient recovers in a few months time.

If the dose is 400 - 450 roentgens the outcome may be fatal in 50% of the cases. This dose is often called the lethal dose. In accordance with this the radius of the area in which there may be lethal irradiation is called the lethal radius.

It is assumed that the overall dose of 550 - 600 roentgens is fatal in all cases.

A characteristic feature of the effect of nuclear radiation on human beings is the relative slowness in development of the changes in the organism. If the doses are very large, there may be so-called ray death occurring at the moment of the actual irradiation. In animals this is not observed until the dose is of the order of 100,000 roentgens, or more, and if the dose is 30,000 roentgens/hour death occurs 30 or 50 minutes after the irradiation commences.

During the atomic raids on the Japanese cities of Hiroshima and Nagasaki in 1945, the number of fatalities due to penetrating radiation was 5 - 15% of the total number of persons killed. Unprotected persons up to 800 m from the epi-center of the explosion were affected by the radiation. Up to 1200 m the number of dangerous cases rose to 50%, but at a distance of more than 2000 m there were no dangerous cases of injury due to penetrating radiation.

As a result of the virtually simultaneous effect of penetrating radiation, shockwave and luminous radiation, most of the destruction was due to

combined factors, and to single out the effect of any one of them on the sickness rate was often impossible.

Some idea of the destructive effect of gamma radiation and neutrons can be obtained from the accidents which have occurred through neglect of the safety regulations. There has recently been a report in the foreign press of two such cases, one occurring at the Nuclear Physics Institute in Yugoslavia (October, 1958), and one at the Los Alamos Scientific Laboratory in the USA (December, 1958).

Experimental research was being conducted in a reactor at the Nuclear Physics Institute in Yugoslavia. A sudden uncontrollable chain reaction caused some staff members standing near the reactor to be subjected to intense irradiation by neutron and gamma rays for brief periods. Measurements and appropriate calculations showed that the average dose received by the victims over the whole organism was about 680 MRE[1]. Forty-three percent of this dose consisted of gamma rays, while the rest was created by neutrons.

An accident occurred in the Los Alamos Science Laboratory in the section in which the waste left over after removal of the plutonium was being cleaned and enriched. A supercritical mass was suddenly formed in the tank into which the waste was being poured, and a fission reaction began. The foreign press reported that one of the staff members received a dose of 12,000 MRE and died 36 hours later, two other persons who received doses of 134 and 53 MRE exhibited signs of radiation sickness.

Soviet literature contains descriptions of two cases of acute radiation sickness, in which the patients received doses of 300 and 450 roentgens. The acute sickness developed as a result of a brief, overall irradiation by gamma rays and neutrons when the regulations for operating experimental piles were violated.

1) Since the victims were at different distances from the center of the reactor, some received a greater dose than others. The given dose is the average.

The course of the illness was described in detail by the doctors who treated the victims at the First International Conference on the Peaceful Use of Atomic Energy[1].

Effective methods of treating radiation sickness are now being developed. An obligatory condition for treatment in a serious case is hospitalization of the patient. Hospitals possess greater possibilities for carrying out the entire set of curative measures.

Common treatment is the use of antibiotics (penicillin, streptomycin, oreomycin and so on). Antibiotics, as it were, compensate for the reduced resistance of the body to infection and are a widely recommended FORM of TREATMENT To counteract the after-effects of radiation sickness. The use of vitamin B_{12} is recommended for restoring the normal composition of the blood, and vitamins P and C plus calcium preparations are recommended for combating hemophilia and to restore the normal metabolism. Diet plays a very important part in the treatment. The food must have a high calory value, it must be easily digestable and rich in albumin and vitamins. Large quantites of drinks are recommended and also the use of diuretic and pseudoirific treatment to speed up the excretion of the radioactive substances from the body. If necessary, there can be blood transfusions, and injection of glucose and vitamin B and C solutions. This is by no means a complete list of some of the methods and means used to cure radiation sickness.

Radius of the destruction area. It has been found that during medium and high power nuclear explosions the shockwave and luminous radiation have a harmful effect over much greater distances from the point of the explosion than the penetrating radiation. But whenever the power of the explosion is relatively small, for example, a thousand tons or less, the penetrating radiation has the greater destructive range.

Effect of penetrating radiation on materials and equipment. Large doses of penetrating radiation (thousands and tens of thousands of roentgens) darken the lenses in optical instruments (SIGHTS, field glasses, rangefinders, etc.). Hence,

-253-

optical instruments must be protected both from mechanical damage from the
shockwave as well as from the effect of penetrating radiation. Photographic film
can detect penetrating radiation at considerable distances since a dose of two or
three roentgen is all that is needed to expose certain types of film.

The effect of nuclear radiation on photographic film was discussed
earlier (see photographic method of measuring gamma radiation); at this point we
will explain briefly why this darkening of the optical glass occurs.

Pierre Curie and Marie Sklodovskaya Curie noted in their time, on the
basis of research, that all types of glass, porcelain and glazed pottery acquire
a violet or brown color in the presence of radioactive substances. It was later
discovered that the change in color was due to variation in the internal structure
and chemical composition of the substance.

The change in the optical properties of glass, which is an amorphous
(non-crystalline) substance, is mainly due to the oxidizing-reducing processes
which occur when there is an exchange of electrons between different ions. The
radiation-induced ionization of the atoms lead to variation in the valence of the
element, and new molecules may be produced as a result. For example, in the
iron oxide molecule Fe_2O_3 the iron atom is trivalent (Fe^{+++}); ionization causes
it to become bivalent (Fe^{++}) and to form a ferrous oxide molecule FeO with the
oxygen. In addition there may be a reverse reaction - the oxidation of Fe^{++}
ions into Fe^{+++} ions. Reactions of this kind may occur in other oxides, for
example, SiO_2.

When many substances are irradiated with neutrons, radioactive atoms
are formed, and there sometimes appear atoms of new chemical elements. This also
causes variation in both the optic and other physical properties of the glass.

There is marked darkening of the optical glass whenever there are a
fairly large number of violations in the structure and composition of a substance,
but for this to happen, as already pointed out, the doses of penetrating radiation
have to be very large.

Penetrating radiation has virtually no harmful effect on military equipment, apparatus or instruments. Damage to materials and equipment is only appreciable when they are subjected to the effect of very large neutron or gamma ray fluxes (of the order of $10^{15} - 10^{20}$ neutrons or quanta per centimeter squared).

Radiation of this kind is only possible at distances from the center of the explosion so short that all objects are destroyed entirely by the shockwave and luminous radiation.

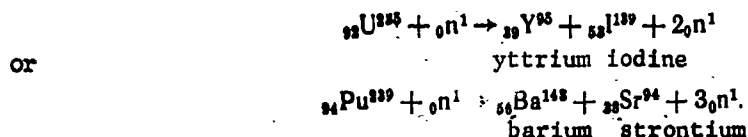## RADIOACTIVE CONTAMINATION DURING NUCLEAR EXPLOSIONS

1. Sources of radiation on terrain contaminated by radioactivity

The locality of the nuclear explosion, the path along which the cloud formed during the explosion moves and also any equipment, people or animals in the open in the locality may be contaminated by radioactive matter.

The radioactive substances contaminating the locality during an atomic explosion consist of the fission products from the nuclear explosion (uranium or plutonium nuclei) artificial substances formed by the effect of the neutrons (induced radioactivity) as well as the unsplit part (that is to say the part which has not been involved in the fission reaction)of the atomic charge. Let us consider in greater detail these three sources of radioactive contamination during an atomic explosion.

Fission products from a nuclear explosive. The fission products (fragments) are a mixture of a large number of isotopes formed from 34 elements starting with zinc and ending with the rare element, gadolinium (see the periodic table). Analysis of the fission products shows that at the fission mainly produces isotopes of elements with mass numbers ranging from 85 to 104 and 130 to 149. Fission into equal parts, which was mentioned earlier, is unlikely. Fission of this kind occurs approximately 600 times more rarely than fission into unequal parts, the mass numbers of which are in the ratio of 2:3. The isotopes of the inert gases, krypton and xenon, the metals strontium, molybdenum, and barium, the isotopes of iodine and antimony, the rare-earth metals lanthanum and cerium and certain other elements are formed in great quantities.

The following patterns of fission are the most likely:

$$_{92}U^{235} + {}_0n^1 \rightarrow {}_{39}Y^{95} + {}_{53}I^{139} + 2_0n^1$$
$$\text{yttrium} \quad \text{iodine}$$

or

$$_{94}Pu^{239} + {}_0n^1 \rightarrow {}_{56}Ba^{148} + {}_{38}Sr^{94} + 3_0n^1.$$
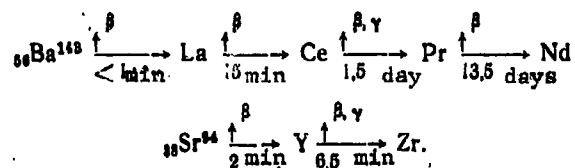$$\text{barium} \quad \text{strontium}$$

The radioactive isotopes of yttrium and iodine, formed during fission, do not turn into stable nuclei immediately. They undergo a small chain of successive beta decays, in a number of cases the ejection of beta particles being accompanied by an emission of gamma rays (Fig. 78). The number of decays accompanied by gamma quanta is approximately 2 or 3 times smaller than the total number of beta decays.

Since there is simultaneous decay of both the fragments produced by the explosion and the products of their decay, within a short period there are about 200 different radioactive isotopes, and a large quantity of stable ones.

The half-life of the radioactive substances obtained are extremely varied and range from fractions of a second to several years.

In confirmation of this we will show the decay chain for a pair of fragments, for example, barium and strontium.

$$_{56}Ba^{143} \xrightarrow[< \text{1 min}]{\beta} La \xrightarrow[15 \text{ min}]{\beta} Ce \xrightarrow[1.5 \text{ day}]{\beta, \gamma} Pr \xrightarrow[13.5 \text{ days}]{\beta} Nd$$

$$_{38}Sr^{94} \xrightarrow[2 \text{ min}]{\beta} Y \xrightarrow[6.5 \text{ min}]{\beta, \gamma} Zr.$$

It should be pointed out that the decay of barium and lanthanum is almost completely over in the first chain within an hour. The radioactive barium is turned into lanthanum. But the lanthanum is radioactive as well; when it decays, it turns into cerium, the half-life of which is $1\frac{1}{2}$ days. In the second chain both the strontium and the yttrium decay very rapidly. The decay is complete within an hour and ends with the occurrence of a stable zirconium isotope.

The overall activity of the fission products an hour after the explosion is determined by the activity of the radioactive isotopes of the following elements: krypton, rubidium, strontium, yttrium, molybdenum, tellurium, iodine, xenon, cesium, barium, cerium, praseodymium, neodymium, promethium, samarium and europium

As has already been pointed out, an atomic explosion produces a mixture of a large quantity of radioactive isotopes. In this case the reduction in
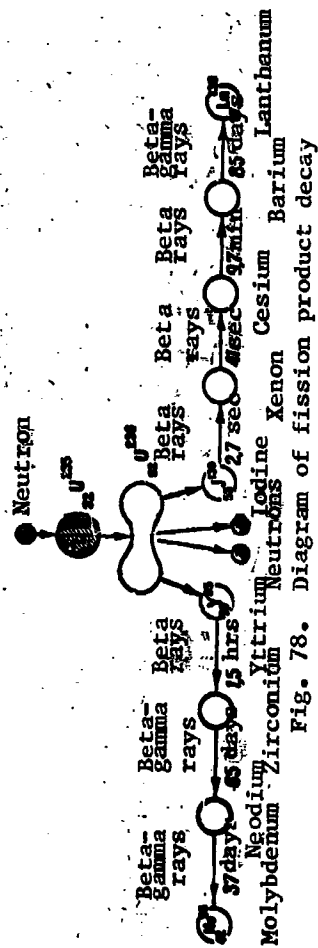
-257-

Fig. 78. Diagram of fission product decay

activity cannot be determined from the law governing the radioactive decay of one particular isotope. The fall in activity of the products from an atomic explosion is calculated by an experimentally derived equation

$$A = A_0 \left(\frac{t}{t_0} \right)^{-1.2} \quad \text{or} \quad A = \frac{A_0}{\left(\frac{t}{t_0} \right)^{1.2}},$$

where A is the activity to be determined after a certain time $\underline{t}$ after the explosion;

A_0 is the activity measured at some other time $\underline{t}_0$.

For the solution of certain problems which do not require a high degree of accuracy we can use the above equation over a wide time range - several minutes to two or three years.

It has been found that one minute after the explosion of an atomic bomb with a TNT equivalent of 20,000 tons the gamma activity of the fission products formed is $8.2 \cdot 10^{11}$ curies. We should point out that the gamma activity means the number of decays per second which are accompanied by gamma radiation.

Let us illustrate with an example the way to use this equation. Let us find what the activity of the fission products will be a day after the explosion of a bomb with a TNT equivalent of 20,000 tons.

In the given case $\underline{t} = 1$ day $= 1440$ min, $\underline{t}_0 = 1$ min and $A_0 = 8.2 \cdot 10^{11}$ curies

$$A = 8.2 \cdot 10^{11} \left(\frac{1440}{1} \right)^{-1.2} = \frac{8.2 \cdot 10^{11}}{1440^{1.2}} = 1.3 \cdot 10^{8} \text{ curies}$$

In the same way we can find the activity at any other moment of time. The table gives results of calculation of the activity with respect to the initial value which is taken at 100%.

A very important practical conclusion can be drawn from these data, namely, that the radioactive contamination is of a relatively unstable nature and that the degree of contamination is constantly decreasing.

Induced radioactivity. Neutron reactions cause the formation of a

Table 24

Relative decrease in activity of fission products (in %)

Activity 1 min later	10 min later	1 hr later	8 hrs later	1 day later	1 week later
100	6,3	0,74	0,06	0,016	0,0016

large number of radioactive nuclei, isotopes of the initial chemical element being formed in radiative capture reactions and new chemical elements being formed in other types of reactions. One such reaction is shown below;

$$_{16}S^{32} + _0n^1 \rightarrow _{15}P^{32} + _1H^1.$$
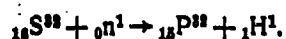
The reaction products may also be non-radioactive. Let us give an illustration of this. Let us assume that a piece of chemically pure iron is subjected to the effect of slow neutrons.

The chemical element iron consists of four isotopes: Fe^{54}, Fe^{56}, Fe^{57} and Fe^{58}. The table given below shows what happens to these isotopes when capturing slow neutrons.

Table 25

Isotope	Abundance in nature	σ_{cap} barns	Capture product	Radioactivity	Half life	Nature of radioactive radiation
Fe^{54}	5,9	0,7	Fe^{55}		2,9 years	Beta and gamma
Fe^{56}	91,6	2,5	Fe^{57}		—	
Fe^{57}	2,2	2,4	Fe^{58}		—	
Fe^{58}	0,3	0,7	Fe^{59}		47 days	Beta and gamma

The table shows that 93.8% of the iron produces isotopes found in nature in the stable non-radioactive state when it captures slow neutrons.

Let us consider the method of calculating induced activity.

If we have a thin plate the surface of which receives a neutron stream of uniform energy, the number of radioactive nuclei N_{act} formed in the plate over an area of 1 cm^2 can be found from the relationship

$$N = \Pi \cdot \sigma_{cap} \, n,$$

where n is the number of atomic nuclei in the material of the plate through which the neutron flux passes.

It is here assumed that all the nuclei capturing neutrons become radioactive. The equation is valid solely for a thin plate, that is to say for a plate of thickness which is such that the energy losses inside it are small. Otherwise, the neutron energy would be modified, and the effective cross-section along with it.

The number of nuclei n can be calculated as follows. Let us determine the weight G of the plate, taking its area to be 1 cm^2, the thickness to be d cm and the density of the material ρ g/cm^3

$$G = d \cdot \rho.$$

Knowing the atomic weight A and the number of atoms in a gram atom, we find

$$n = 6.02 \cdot 10^{23} \frac{G}{A} = 6.02 \cdot 10^{23} \frac{d \cdot \rho}{A}.$$

Then

$$N_{act} = 6.02 \cdot 10^{23} \frac{d \cdot \rho}{A} \Pi \cdot \sigma_{cap}$$

To find the activity, that is to say the number of atoms decaying in one second, we must know the decay constant λ.

$$a = \lambda \cdot N_{act} \text{ but } \lambda = \frac{0.693}{T}.$$

Consequently,

$$a = 6.02 \cdot 10^{23} \frac{d \cdot \rho}{A} \Pi \cdot \sigma_{cap} \frac{0.693}{T}.$$

This is how we find the number of decays per second. If we are required to express the activity in curies, the number of decays has to be divided by $3.7 \cdot 10^{10}$.

We finally arrive at a relationship for the activity induced in a plate of area 1 cm^2

$$a = 1.12 \cdot 10^{13} \frac{d \cdot \rho}{A} \frac{\Pi \cdot \sigma_{cap}}{T},$$

where T is expressed in seconds.

-260-

Let us solve an easy problem.

A flux of slow neutrons $\Pi = 10^{10}$ neut./cm^2 impinges upon an aluminum plate $\underline{d} = 0.1$ cm with an area $\underline{S} = 1$ cm^2. We are required to determine the induced activity, given the premise that the reaction causes the formation of an isotope with a mass number $A = 28$ and a half-life $T = 2.3$ min.

For aluminum

$$\sigma_{cap} = 0.21 \cdot 10^{-24} \ \text{cm}^2; \quad \rho = 2.7 \ \text{gr/cm}^3$$

Then,

$$a = 1.12 \cdot 10^{13} \, \frac{0.1 \cdot 2.7 \cdot 10^{10} \cdot 0.21 \cdot 10^{-24}}{2.3 \cdot 60} =$$

$$= 0.0000016 \ \text{curies or } 1.6 \ \text{microcuries}$$

The derived equation gives us the activity of an isotope immediately after neutron bombardment, or in other words, immediately after an atomic explosion. As time passes, the activity constantly decreases. In order to take the radioactive decay to account, we have to add the following multiplier to the equation.

$$e^{-\lambda t} = 2^{-t/T} = \frac{1}{2^{t/T}}.$$

Then we get

$$a = 1.12 \cdot 10^{13} \, \frac{d\rho}{A} \, \frac{\Pi \sigma_{cap}}{T} \, \frac{1}{2^{t/T}},$$

where $\underline{t}$ is the time which has elapsed since the neutron irradiation began.

All the arguments and equations given above hold for substances consisting of a single isotope. There are comparatively few such substances. They include sodium, aluminum, phosphorus, manganese, cobalt, iodine, cesium and certain other less common elements.

Most chemical elements consist of several isotopes. That is still not all. We rarely come across chemical elements in the pure form. Practically all the bodies surrounding us are compound, that is to say they consist of several chemical elements. When determining the activity induced by neutrons in a chemical element consisting of several isotopes, we should keep it in mind that all the

-261-

isotopes possess different powers of neutron capture and as a result produce radioactive nuclei with different half-lives. Hence we must make the activity calculation for each isotope separately and take into account the content of it in the given element.

If the substance is a chemical compound, we have to take into account the content of the chemical element in the given substance. For example, in alloyed steel we even have to consider comparatively small additions of such elements as manganese, nickel, chrome, molybdenum, since they are easily activated.

Neutrons released during an atomic explosion interact with the nuclei of chemical elements making up the air, soil, water and various installations on the ground. As a result of the atomic nuclei capturing the neutrons, they form radioactive isotopes which, as they decay, emit beta and gamma rays.

                                                          are
In the air, as has already been mentioned, the neutrons/only absorbed by nitrogen for practical purposes, and the two substances formed are nitrogen 15 and carbon 14. Nitrogen 15 is found in nature in small quantities. This isotope is not radioactive. Carbon 14 is a slowly decaying radioactive isotope; by combining with oxygen in the air it produces carbon dioxide which is assimilated by vegetation in exactly the same way as carbon dioxide with non-radioactive carbon.

The first compound on the list in the chemical composition of the soil is silica SiO_2, and it is followed in descending order by Al_2O_3, Fe_2O_3, K_2O, Na_2O, MgO and CaO, together with various organic matter in the upper layer.

The induced radioactivity is not only found in the surface layer, but also at some depth. It is difficult, however, to take this into account by the simpler calculation methods since the neutron flux and neutron energy are continually changing as they penetrate deeper and deeper.

Let us now consider which substances are contained in sea and river water. As is known, there is no completely pure water in nature. Being a good solvent, water dissolves the matter with which it comes in contact and carries it

along with it. A liter of ocean water contains an average of 33 to 39 g of dissolved solids, including 24 g ordinary salt. There is also salt in river water, but only a very small proportion.

The salts contained in sea water are distributed approximately as follows: 78.4% cooking salt; 9.4% magnesium chloride (MgCl); 6.4 magnesium sulfate (MgSO); 3.9% calcium sulfate ($CaSO_4$); 1.7% calcium chloride ($CaCl_2$) and about 0.2% of various other salts. Thus, sea water contains mainly sodium, chlorine, magnesium, calcium and sulfur.

The induced radioactivity in water is determined by the content of sodium and potassium salts.

The induced radioactivity in food products is not very high. Exceptions to the rule are products containing a large amount of common salt. Packing material used to wrap food products may also become radioactive, glass acquiring the greatest degree. But the effect of induced radioactivity on the degree of contamination of packing material, as a rule, is less than the effect of radioactive fallout.

A large number of the artificially radioactive isotopes have comparatively short half-lives, hence an increase in the radioactive contamination through this may be observed during the first few hours (sometimes day) following the explosion.

The most substantial contribution to gamma radiation of the activated earth during the first few minutes after the explosion is provided by aluminum (T = 2.3 min), after which, for the first few hours, came manganes (T = 2.6 hr) and sodium (T = 15 hr), and then after 200 hours iron (T = 47 days).

The non-reacted part of the atomic charge. We know that during an atomic explosion only a certain part of the material of the charge takes part in the chain reaction. The non-reacted matter in the charge is evaporated, is scattered in the atomic cloud and falls onto the ground together with the fission products.

The nuclear explosives - uranium and plutonium - are alpha-active

-263-

elements, hence as soon as they have settled on the ground the particles become sources of alpha radiation. But the activity, both in uranium as well as plutonium is very small compared with the activity of the fission products, since both uranium and plutonium possess a long half-life. For example, supposing the weight of the unexploded portion of the charge is 10 kg, its activity is 600 curie for plutonium and 0.02 curies for uranium 235.

The extent of this activity is negligible compared with the fission fragments. Hence contamination of a locality by uranium or plutonium is of no practical importance.

Radiation of radioactive products from an atomic explosion. The radioactive matter falling onto a locality from the atomic cloud as well as the matter formed over the locality by the action of neutrons emit alpha particles, beta particles and gamma rays. Let us consider the characteristics of radiation emitted by the radioactive products.

Alpha radiation. Alpha particles are emitted during radioactive decay of the non-reacting part of the atomic charge.

Alpha radiation presents the greatest danger when alpha-active material gets inside the human body.

Beta radiation. Beta particles are emitted by the fission products and artificial radioactive elements formed by the neutrons. Given the same energy, the ionizing power of beta particles is much less than for alpha particles, while the path in substances is correspondingly greater. For example, beta particles with an energy of 2 Mev have a maximum path in the air of about 10 m, in water about 1 cm, and in lead lessthan 1 mm. It is very rare that beta particles are emitted with energy more than 2 Mev.

Human beings sheltering in buildings are entirely protected from the effect of beta radiation emitted by the radioactive matter falling outside. Clothing also absorbs a lot of beta radiation. Hence external irradiation by beta particles is no great danger provided the radioactive material does not

came into contact with the open integuments, particularly the mucous membranes of the eyes, nose and mouth. Beta particles are very dangerous when the radioactive matter emitting them gets inside the organism.

Gamma radiation. Gamma radiation is emitted on a radioactive contaminated locality during the decay of some of the fission fragments and artificial radioactive substances. In the given case the mean gamma radiation energy, which is about 0.7 Mev, is less than that of the penetrating radiation. Since the gamma radiation is continually weakened as the energy decreases, the thickness of the layer required for protection from gamma radiation in a contaminated area is naturally less than for protection from penetrating radiation.

Calculations show that to weaken the gamma radiation with an energy of 0.7 Mev by a factor of 2, we need a layer of lead 0.8 cm thick, or a layer of concrete 7.5 cm thick. In the middle of the first floor of a two-story house in a built up area, the radiation level is approximately 40 times lower than on open terrain. Slit trenches with an earth cover 30 cm thick reduce the radiation level by approximately a factor of 100.

On the basis of these data we can assess the degree of weakening of gamma radiation by different types of shelters and constructions located in a contaminated locality.

2. Radioactive contamination during different types of atomic explosions

Fallout of radioactive material from an atomic cloud. In still weather the mushroom cloud appears as shown in Fig. 10. When there is wind, the cloud drifts and the column of dust (stalk of the mushroom) becomes curved. When the cloud stops rising, it continues moving in the direction of the wind blowing at that particularly height, and at the same speed.

It should be pointed out that as the height increases, the direction of the wind is no longer constant, but deviates first to the left, then to the right, and sometimes even reverses its direction. The speed of the wind also varies.

For example, in one region the average speed of the wind over the year near the ground was 5 m/sec while at an altitude of 4 km it was about 13 m/sec.

Since the radioactive products are very finely atomized during the explosion, they are carried up to the upper layers of the troposphere or even into the stratosphere, and are shifted by the air currents a long way from the point of the explosion.

The radioactive particles in the cloud collide with particles of earth - dust - which are usually larger than they are, and adhere to them. This produces radioactive dust which gradually settles along the path taken by the cloud.

The cloud leaves a "trail" along the ground, i.e., a long narrow strip of terrain contaminated by radioactive matter.

The rate at which the dust particles settle depends on their density and size. If we take the density to be more or less uniform, the rate of fall is determined by their size. The larger the particle, the faster it settles on the ground (see Table 26).

We should point out that particles with a diameter of 0.005 - 0.010 mm are considered medium dust, particles of coarse dust possess diameters ranging from 0.010 - 0.050 mm, particles 0.05 - 0.25 mm are classed as fine sand, and finally, medium sand constitutes particles with a diameter of 0.25 - 1.0 mm.

Table 26

Time taken by dust particles to settle from altitude of 12 km

Particle diameter, mm	Settling time
0.84	22 min
0.25	42 min
0.15	2 hours
0.075	7.9 hours
0.033	1.7 day
0.016	7 days
0.008	28 days

Let us see to what extent the radioactive fission products fall out together with the dust. It seems that only about 4% in all falls out with the coarser dust particles, of which there are comparatively few in the mushroom cloud

(within 22 minutes), about 13% fall out during the next 20 minutes, and 14.5% radioactive material settles over a period from 42 minutes to 2 hours.

Thus, about one-third of the radioactive matter formed by the explosion falls out during the first two hours. The remainder stays in the air for a much longer period.

Particles of fine dust 1 micron in diameter (0.001 mm) and density 3 g/cm^3 settle at the rate of 0.6 cm/min. This is so slow that the dust may be transported virtually anywhere in the world by the wind or even go right around it. Thus the presence of radioactive products, although they may be extremely small in quantity, can be detected at great distances from the point of the explosion.

To take radioactive samples at ground level we use filtering devices with a fairly high throughput, and various TYPES OF boards with sheets of sticky paper are ALSO commonly used to collect radioactive fallout. Furthermore, filters installed aboard aircraft are used totake samples of air together with the dust contained in it. Measurement of the activity of the filter and analysis of the samples is carried out in radiometric laboratories. Systematic observation of the air and fallout enable us to detect nuclear explosions. For example, after the explosions at Bikini in 1954, the radioactivity of rainwater sharply increased at several places in Japan.

If we set up special equipment at control points at intervals of 2 or 3000 km, an explosion with a power of 1000 tons carriedout in the troposphere can be reliably detected within 5 - 20 days, the time of the explosion also being determined, though with some inaccuracy. In certain cases we can determine the approximate place of the explosion if we know the meteorological data needed to find the trajectory of the radioactive cloud and the dust particles.

Degree of radioactive contamination. The degree of contamination as well as the size of the contaminated area depend on the type of the explosion, the caliber of the charge and the meteorological conditions, the nature of the terrain

and the soil. The direction and speed of the wind have a considerable effect on the degree of contamination of the different areas of the locality and surfaces of different objects.

The degree of contamination of the locality and the size of the contaminated area decrease all the time as a result of the decay of radioactive matter as well as the fact that they are blown over the surface of the ground by the wind, washed away by rain or enter the soil.

The degree of contamination of a locality is most conveniently described by the <u>radiation level</u>, which is measured in roentgens per hour[2].

By knowing the radiation level, we can restrict the external irradiation dose, which is determined basically by the effect of gamma radiation. However, in cases in which radioactive material may enter the human organism, this is quite inadequate. In order to rule out the possibility of injury through internal irradiation, we must know the concentration of radioactive material in water, air, food products and also on the surface of the things with which we come into frequent contact, (equipment, arms, armored vehicles, etc).

This is why there is a second characteristic for describing the degree of radioactive contamination - the density of the contamination - which is measured by the number of decaying atoms per minute per unit volume, unit weight or unit surface (abbreviated to: k/min, liter, or $decay/min \cdot cm^2$). This takes into account all the beta decays, including those which are not accompanied by gamma radiation.

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[1]
Negotiations on the cessation of nuclear tests (documents). Supplement to "New Times" No. 36, Sept. 5, 1958.

[2]
In the case of radioactive contamination the term "radiation level" is used much more frequently than "dose rate", although they mean the same thing.

-268-

Thus, the presence of two characteristics for describing contamination is due to the two possible ways that radioactive radiation may affect human beings: irradiation or the contamination of the integuments by radioactive matter (external irradiation) and penetration inside the body (internal irradiation).

There is a definite relationship between the contamination density and the radiation level.

Let us imagine a completely smooth flat surface uniformly contaminated by radioactive matter.

Radiation levels above the surface is proportional to the contamination density and is a function of the height of measurement and size of the contaminated area. The way in which the size of the area affects the radiation level when the density is constant is shown in Fig. 79. At first there is a sharp increase in the radiation level as the radius of the area is increased, but then the increase becomes slower. For example, at the center of an area with a radius of 10 m radiation level at a height of 1 m is approximately 50% of the total possible, which occurs in the case of an area of infinite radius.

As the height of the measurement point is increased, (for example, in aerial radiation detection) the part played by areas further away is increased. Supposing for example, the height H = 50 m, the radius of the area over which the radiation level is 50% of the maximum is increased to 100 m.

It should be kept in mind that in the case of a natural surface, such as an open field, the radiation level measured at a small altitude is less than the theoretical value because of the screening effect of the slight unevenness of the ground.

Calculations show that at a contamination density of 1 curie/m the radiation level in the middle of a fairly large area is 5 roentgen/hour (H = 1 m). But if the degree of contamination is reduced by a factor of 1000 (220,000 decay/cm^2 min), the level is also decreased 1000 times and becomes 0.005 roentgen/hour.

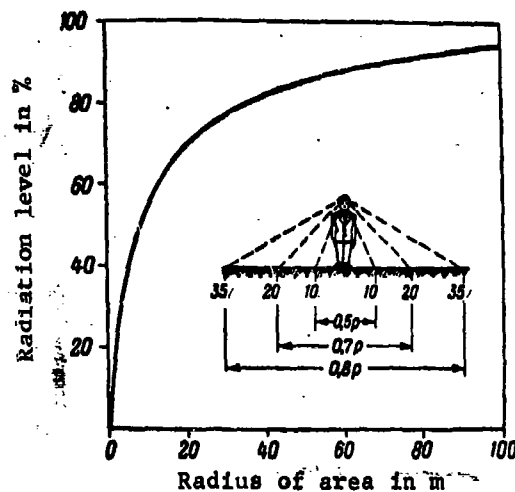The mean gamma ray energy is taken as 0.7 Mev for the calculations.

Fig. 79. Variation in radiation level with increase in size of contaminated area.

Radioactive contamination during an aerial atomic explosion. During an explosion in the air at a high altitude the bulk of the fission products are swiftly carried aloft by the ascending cloud. The radioactive contamination in the vicinity of the explosion is only slight since only a few hundredths of a percent of the fission products fall out onto it. The remainder is scattered over a wide area in the "wake" of the cloud and is of no danger. Contamination in the vicinity of the explosion is chiefly governed by the induced radioactivity. But this activity, too, is only slight, since the number of neutrons close to the ground decreases rapidly as the distance from the center of the explosion is increased. Furthermore, the radioactive substances formed in the ground decay fairly soon, hence strong contamination is observed for a short time afterwards. After several tens of minutes have elapsed, troops may operate in the vicinity of the epicenter without any risk of contamination.

It is known, for example, that during the explosions in Japan there was very little radioactive contamination of the terrain or the buildings in the cities. During the aerial explosions near Bikini in the summer of 1946, the contamination of the ships by radioactive material was similarly of little importance.

-270-

Radioactive contamination during a ground level explosion. When the explosion occurs in the air at a low altitude, the contamination is greater. In this case the fireball comes into contact with the surface of the earth. The crust of the soil is fused, mixes with the explosion products and flung in all directions by the shockwave. Much of the radioactive material from the explosion stays in the contaminated area in the form of radioactive slag. A great deal of dust and fine slag particles with the radioactive atoms which have settled on them is swept up into the cloud.

The mean size of the soil particles drawn into the cloud during a ground level explosion is considerably larger than in an aerial blast.

As the cloud rises, some of the coarser particles of dust and slag fall out onto the ground in the vicinity of the explosion, stepping up the radioactive contamination of the locality round about   . The fall out continues in the path of the moving cloud, as well, causing the formation of a narrow strip of contaminated terrain several km wide and several tens of km or more in length, according to the power of the explosion.

Fig. 80 shows how the distribution of the radiation levels in the region of a ground level explosion varies with time. The data are characteristic of cases in which the explosion occurs during moderate wind and without rain. Close to the center of the explosion the terrain is strongly contaminated, but the area of contamination is comparatively small.

It is quite possible to MOVE/ THROUGH the contaminated area (towards the center) in this case, too. Calculations show that at a velocity of motion of 50 km/hour an hour after the explosion the maximum possible dose is not greater than the dose permissable for single radiation.

The radiation level depends on the flux density of the gamma quanta (number of quanta per 1 cm sec) and their energy. The energy changes only slightly with time, while the number of gamma quanta decreases in direct proportion to the reduction in activity. Hence variation in the radiation level over the contaminated terrain is not determined very effectively by the same law as for the

-271-

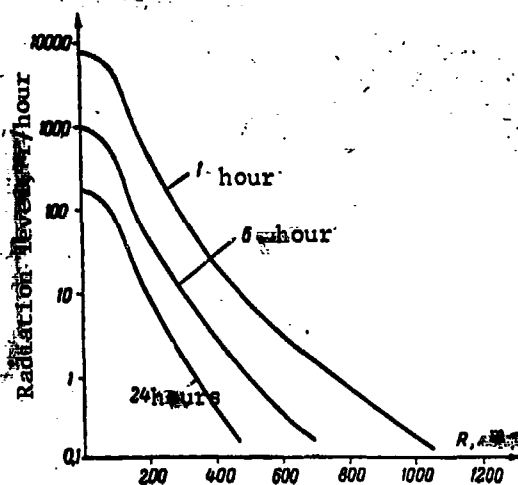Fig. 80. Variation in radiation levels with distance for ground level
explosion (q = 20,000 tons).

variation in activity, to wit

$$P = P_0 \left(\frac{t}{t_0} \right)^{-1.2},$$

where P_0 is the radiation level at a moment t_0 after the explosion;

P is the radiation level at the moment of time t .

The level six hours later has decreased by a factor of 9, and a day
later by a factor of 46, compared with the radiation level an hour after the ex-
plosion.

The total dose received over the time from t_1 to t_2, for example over
the time spent in the contaminated area when t_1 may be the moment of arrival in the
area, that is to say the beginning of the irradiation, and t_2 is the moment of
disappearance, that is to say the end of the irradiation, is determined by the
following equation

$$D = 5Pt^{1.2} \left(\frac{1}{t_1^{0.2}} - \frac{1}{t_2^{0.2}} \right) \text{ roentgens}$$

where P is the radiation level measured at the moment t;

t_1 and t_2 are the times of commencement and completion of the irradiation.

In this equation t, t_1 and t_2 are measured in hours, beginning at the moment of explosion.

If the commencement of the irradiation coincides with the moment that the radiation level is measured, that is to say if $t = t_1$, the equation given above can be written down in a slightly different form, i.e.,

$$D = 5P_1 t_1 \left[1 - \left(\frac{t_1}{t_2} \right)^{0.2} \right],$$

where P_1 is the radiation level measured at the moment t after the explosion;

D is the radiation dose received between the time t_1 and the time t_2.

If t_2 is slightly larger than t_1, the total dose (designated D_{max}) is calculated from a simpler equation

$$D_{max} = 5P_1 t_1 \text{ roentgens}$$

This dose may be obtained over a long period in the contaminated zone.

Hence the maximum possible dose over a very long period of irradiation cannot exceed D_{max}. If the radiation level is, say, 10 roentgen/hour six hours after the explosion, than $D_{max} = 300$ roentgens.

Let us assume for the sake of convenience, that the irradiation began an hour after the explosion ($t_1 = 1$ hour) and $P_1 = 1$ roentgen/hour. The doses calculated for this case when the irradiation lasts t time are shown in Table 27.

Table 27

Variation in gamma radiation dose with time (radiation level one hour after explosion is 1 roentgen/hr)

t	6 hours	12 hours	1 day	2 days	7 days	30 days	
D roentgen	1,5	2,0	2,4	2,7	3,2	3,8	

Naturally, if the initial radiation level is not 1 roentge/hr, but, let us say 10 roentgen/hr, the doses are increased accordingly by a factor or 10.

Fig. 81 shows how the dose accumulates over different irradiation times taking 100% as a dose obtained when the time spent in the contaminated locality is infinitely long, and that the irradiation begins an hour after the explosion.
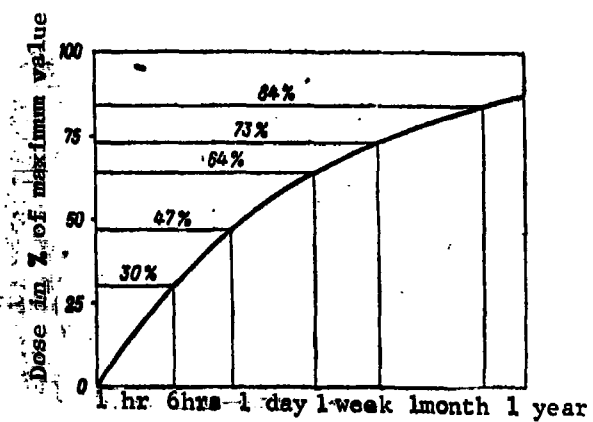
Fig. 81.   Dose as a function of time spent in the
contaminated locality

It can be seen from the figure that considerable amounts of the total dose - about 50% - is obtained by the organism during the first few days, after which the accumulation slows down somewhat.

During a ground level explosion, a large amount of radioactive dust falls out in the form of a trail left by the cloud. It is possible for terrain a long way away from the explosion to be contaminated. For example, during the Alamogordo tests strong radioactivity was recorded several miles to the north and east of the explosion point. But the total dose was harmless. It was reported that radioactive dust fell on the body surface of several animals 16 to 24 km from the explosion. Several weeks later they developed ulcers at various places and the ulcers soon healed and the effected areas underwent complete recovery.

The length and shape of the radioactive "trail" depends on the speed and direction of the wind at different heights. A trail in the form of an elongated ellipse is formed on open country when the direction of the wind is constant at all altitudes in which the radioactive dust passes by. However, we must take into account the possibility of a change in the direction of the wind at certain heights. In this case the shape of the trail is also changed.

During a ground level explosion, approximately 65 - 90% of the radioactive fission products fall out in the region of the explosion. The area of local contamination depends on the nature of the ground, which determines the amount of dust thrown into the air and the size of the dust particles, as well as the meteorological conditions at the moment of explosion, since these determine the direction of the radioactive dust and the distance over which it is carried before managing to settle on the ground. The area of dangerous contamination for a groundlevel explosion of intermediate power may be of the nature of 250 km^2.

The table below gives approximate data on the radioactive contamination for the groundlevel explosion of an atomic bomb with a TNT equivalent of 20,000 tons. The mean wind velocity 24 km/hr. The radiation levels were determined an hour after the explosion with complete fallout of the radioactive products.

-274-

Table 28

Radioactive contamination by a groundlevel explosion[1]

Radiation level roentgen/hour	Distance from center of explosion, km		Width of cloud trail km
	windward	leeward	
3000	0,16	1,8	0,6
1000	0,35	3,7	1,1
300	0,66	8,3	1,9
100	1,06	18,5	2,9
30	1,50	35,0	4,5
10	2,20	80	8,1

The commencement of the falling out of radioactive dust onto the ground from the atomic cloud over the distance R from the explosion when the speed of wind V is moderate[2] can be determined approximately by dividing R by V. For example, supposing V = 20 km/hr, and R = 40 km, the fallout of dust in this region begins approximately 2 hours after the explosion. During the settling time the activity of the radioactivity matter is considerably decreased through spontaneous decay.

Fig. 82 shows how different factors effect the fallout. As the height to which the particles of equal size ascend is increased, the distance from the explosion point over which they obtain the earth's surface (Fig. 82A) also increases. Here the horizontal movement of the coarser particles is considerably less than that of the finer particles falling from the same height (Fig. 82B).

If the wind speed is increased at all heights as shown in Fig. 82C , the range of the fallout is also increased. The bottom drawing in the figure (Fig. 82D) is a diagram of the path of a particle varying in direction and magnitude (the direction of the wind is shown by an arrow and the length of the arrow is the force of the wind).

[1] "The Effects of Nuclear Explosions", Washington, 1957.

[2] A moderate wind is a wind whose direction and speed are mean for the whole system of winds affecting the radioactive particles when they move towards the earth.
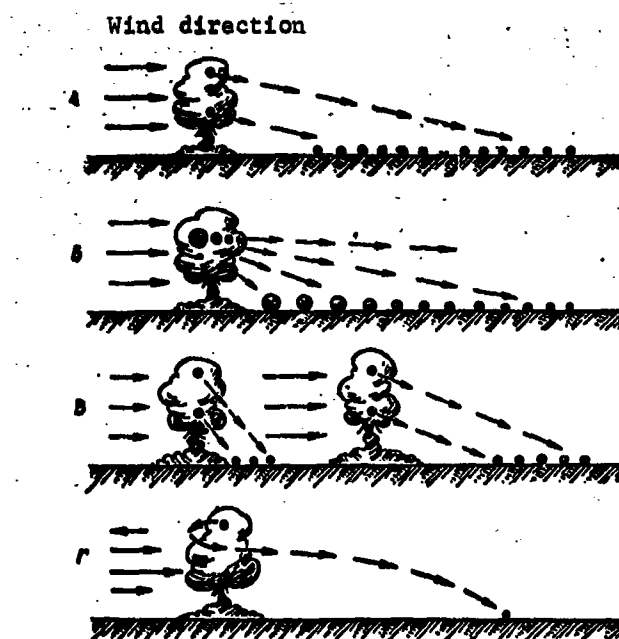
Fig. 82. Distance to a point of explosion over which radioactive particles reach the ground from their altitude of ascent (A) as function of particle size (B) and nature of the wind (C) and (D).

The basic nature of phenomena involved in the fallout of radioactive matter during a ground level explosion does not in effect depend on the power of the explosion. But the amount of radioactive fission products is proportional to the TNT equivalent of the atomic charge. This fact gives us a very simple relationship between the radiation level and the power of the explosion

$$P_1 = P_2 \sqrt[3]{\frac{q_1}{q_2}} \text{ at } R_1 = R_2 \sqrt[3]{\frac{q_1}{q_2}}.$$

In these equations P_2 is the radiation level at a distance R_2 an hour after a groundlevel explosion of an atomic charge with a TNT equivalent q ; P_1 is the radiation level at a distance R_1 an hour after the explosion of the charge q_1.

When atomic charges of a TNT equivalent of less than 100,000 tons are exploded, foreign specialists recommend data for radioactive contamination for the explosion of a TNT equivalent of 20,000 tons as A basis OF calculation .

The approximate relationships given above enable us to make some practical

calculations more simple. Let us illustrate this with an example.

Example. The TNT equivalent of an atomic charge during a ground level explosion is q = 75 kt. The medium wind speed is 24 km/hr. We are required to determine the radiation level created over an area 55 km from the center of the explosion in the direction of the wind at the moment of fallout of the radioactive matter.

Solution. Table 28 shows the radiation levels created when an atomic bomb with a TNT equivalent of 20,000 tons is exploded. The known quantities in this case are $q = 75$ kt, $q_1 = 20$ kt, $R_1 = 55$ km. Let us find R_2.

$$R_2 = \frac{55}{\sqrt[3]{\frac{75}{20}}} = 35 \text{ km}$$

According to the table, at this distance $R_2 = 30$ roentgen/hr, so $P_1 = 30 \sqrt[3]{75/20} = 46$ roentgen/hr. But the derived radiation level could have occured 55 km an hour after the explosion, whereas the problem we are set is to determine the radiation level at the moment of fallout of the radioactive explosion products, that is to say $t_{sup} = 55/24 = 2.3$ hrs later. Over this period the radiation level will have fallen slightly to P on account of decay of the falling products

$$P = P_1 t_{fallout}^{-1.2}$$
$$P = 46 \cdot 2.3^{-1.2} = 17 \text{ roentgen/hour}$$

So this is the radiation level which will be observed at the given point immediately after fallout.

If the mean wind speed were doubled, the distance over which we could expect this level of radiation would be approximately doubled as well.

Underground explosions. The characteristic feature of an underground atomic explosion is the formation of a large crater and the ejection of a great amount of soil. Some of the soil falls back into the crater, but the bulk of it is thrown all round. The size of the crater depends on the depth at which the bomb was exploded, on the power of the explosion and on the properties of the soil.'

-277-

An underground explosion results in very strong radioactive contamination of the locality adjoining the site of the explosion, since the radioactive matter is flung about together with the soil over a comparatively wide area; an especially large amount is left in the crater.

The radioactive explosion products mix with the soil when the latter is ejected, so that they may be detected both at the top and bottom of a pile of ejected earth. But the gamma rays coming from the bottom of the pile are strongly weakened by the time they merge. A characteristic feature of radioactive contamination during an underground explosion is the fact that a large part of the radioactive matter formed is buried in the ground and cannot have a harmful effect.

The effect of the thickness of a layer of contaminated ground on the radiation level above it (height of measurement 1 m) when the radioactive matter is evenly distributed through the layer is shown in Fig. 83. In this case the mean energy of the gamma rays is taken as 0.7 Mev and the size of the area is taken as fairly large. The graph in Fig. 83 shows that at the top of a layer 5 cm thick the radioactive matter produces approximately 70% of the maximum radiation levels; the next 5 cm at 18%, and only 12% is added after this. Thus, the radiation level is almost entirely determined by the gamma radiation issuing from a layer of comparatively slight thickness.

It should be noted that when the measurements are taken a short way above the layer of active soil ($H = 1$ m), the radiation level little depends on the radius of the layer. Areas of the soil more than 10 m away from the point of measurement only constitute 10% of the total radiation level.

The thickness of the layer may vary slightly in accordance with the density of the soil. Furthermore, the distribution of radioactive matter in the soil thrown up may be non-uniform; there is obviously more of it in the upper layer than at the bottom.
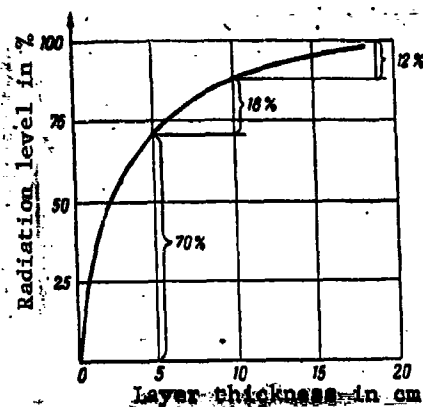
Fig. 83. Radiation level above radioactive layers of different thickness.

If an explosion occurs in ordinary soil not too far below the surface, there may be a dust wave in the form of a dust cloud moving over the surface of the earth in the direction of the wind. The wave may create strong radioactive contamination at considerable distances from the point of the explosion.

The radiation level for an underground atomic explosion is greatly affected by the induced radioactivity, particularly in the crater or nearby it. During the first few moments after the explosion the radiation level in the crater may be hundreds of thousands of roentgens an hour.

In the vicinity of the crater formed by an underground explosion we can EXPECT just about the same contamination as for an explosion on the ground, / PROVIDED the explosions conditions are the same. But the total area of contamination in the first case is considerably less than in the second.

It is dangerous to stay for any length of time in the vicinity of the crater, apparently for several weeks.

Underwater explosion. In an explosion under the water, just as underground, almost all the radioactive fission products stay in the water. The degree of contamination depends on the depth of the explosion, the nature of the reservoir, the meteorological conditions, and so on. The radioactive contamination of the water is further increased by the fact that the neutrons create artificial radio-

-279-

activity in several elements making up the seawater salts. The stability of the contamination is greater than in an explosion above water, but lower compared with an underground explosion. The reduction in intensity of the contamination is not only due to the radioactive decay, but also to the mixing of the contaminated water with the clean water round about and the precipitation of radioactive particles onto the bottom of the sea or lake.

An underwater explosion, as we know, is accompanied by the formation of a base wave. The propagation of this wave and the fallout of radioactive rain in the vicinity of the explosion contaminate various objects on the surface of the water. Radioactive water may render a harbor or estuary temporarily useless; the coastal regions may also become contaminated.

The currents of the base wave is due to the presence of moist masses of air in the vicinity of the explosion. Foreign literature contains comments to the effect that the base wave may not occur if the dry air masses are proponderant during the underwater explosion.

The radioactivity of water after an atomic explosion in the case of Bikini (depth of explosion 8 - 9 m) is shown by the data in the table below[1].

If the contaminated zone is crossed four hours later at a speed of 36 km/hr, the maximim possible dose which could be received is not more than 15 roentgens.

But it would be dangerous for a ship to remain any length of time in the contaminated region for the first one or two days.

Radioactive contamination of air. The radioactive matter from an atomic explosion not-only contaminates the locality and all objects located on it, but also the air. The contamination of the air by radioactive dust near the surface of the earth depends to a large extent on the meteorological conditions, the vegetation and state of the ground. Apart from dust, air contains gaseous explosion products, particularly the radioactive inert gases xenon and crypton. These isotopes, however,

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[1] "The Effects of Atomic Weapons", New York-London, 1950.

Table 29.

Radioactive contamination during underwater explosion.

Time since explosion hour	Mean diameter of contamination zone, km	Maximum radiation level roentgen/hour
4	7,4	75
38	7,7	10
62	12,6	5
86	14	1
100	15	0,6
130	18,7	0,2
200	23	0,01

have a comparatively short half-life and their activity declines rapidly with time.

The bulk of the radioactive matter, including the gases, are contained in the atomic cloud formed during the explosion. The atomic cloud is a powerful source of beta and gamma radiation.

The height to which the atomic cloud ascends depends on the power of the explosion, the temperature gradient and density of the surrounding air. During the nuclear tests with charges of several million tons, carried out in the USA in 1952 and 1954 in the Pacific, the top of the cloud, as reported by the foreign press, rose to a height of 30 or 40 km.

Approximate data on the height of ascent and the size of the atomic cloud are shown in Table 30.

Table 30.

Height of ascent and size of atomic cloud as function of power of explosion

TNT equivalent 1000 tons	Height of ascent of cloud, km	Thickness of cloud km	Diameter of cloud 10 min after explosion km
.2	3	1	2
10	6	2	3
100	12	5	10
1000	19	8	30
10000	25	14	—

If an aircraft flies through the cloud, the crew is subjected to the effects of radioactive radiation. The irradiation dose is determined, first, by

-281-

the gamma radiation of the radioactive matter contained in the cloud and, second, by the gamma, beta and alpha radiation of the contaminated air entering inside the aircraft, and, third, by the gamma radiation of the radioactive matter left on the aircraft after emerging from the cloud.

The effect of the gamma radiation from the cloud on the crew, or in other words, the degree of external irradiation, depends on the radiation level in the cloud, the duration of the flight and the direction of the flight with respect to the cloud center. The radiation level in the cloud is constantly decreasing on account of the decay of the radioactive matter and fallout onto the ground. As has already been mentioned, the size of the cloud formed during the explosion increases all the time, being spherical for the first few minutes after the explosion and then becoming elongated in the direction of the wind, forming an oval. The *longer* the time *since* the explosion, the more blurred the outline of the cloud becomes on account of air currents and the more complex its shape. An hour after the explosion of an atomic bomb with a TNT equivalent of 20,000 tons, the volume of the cloud has attained 300 km^3. If the radioactive matter is distributed uniformly in the cloud, the specific activity is approximately equal to 0.02 millicurie per liter.

During the explosion of a 20 million ton bomb, the volume of the cloud is approximately 10,000 km^3 an hour after the explosion, and the mean concentration of radioactive matter in it is approximately 0.7 millicurie per liter. Inhalation of this air could have serious consequences.

The radioactive matter is distributed non-uniformly through the cloud, hence the radiation level, too, is not constant. Fig. 84 shows a possible graph for variation in the radiation level according to the section of the cloud. If an aircraft flies through the cloud, even though it may be slightly off center, the

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1)
  Based on data from the book "Meteorological and atomic energy" Translation from English. For. Lit. Press, 1959.
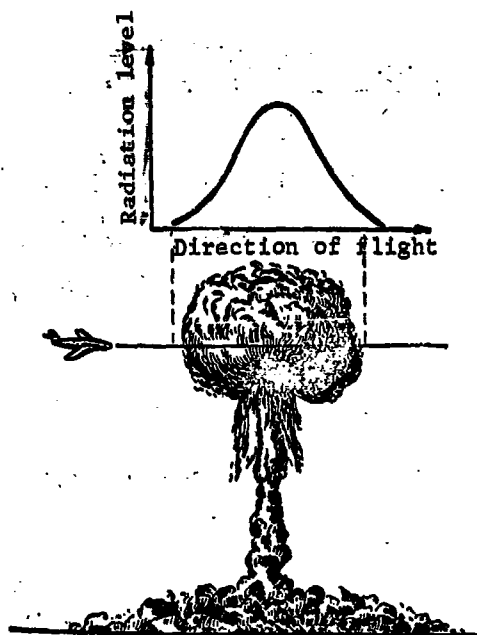
Fig. 84. Approximate graphs for variation in radiation level according to diameter of atomic cloud.

radiation dose is considerably less. If we assume that the radioactive matter is distributed evenly though the cloud, the radiation level is maximum at the center; it is approximately half as much the time it reaches the outer boundary of the cloud.

Data quoted in the press suggest that the dose received by the crew flying for 1 or 2 minutes through a radioactive cloud is less than the permissible dose, provided about an hour has passed since the explosion. But even in the event that the flight occurs half an hour after the explosion, the dose throughout the flying time is less than the permissible dose for a single irradiation. The dose will also depend on the design of the aircraft, since gamma rays may be absorbed by parts of the aircraft, fuel tanks, engine and so on.

A flight through the base of the cloud (dust column) is safe. The diameter of the column is less than that of the cloud, hence the duration of the radiation is less; furthermore, the concentration of radioactive matter in the dust column is only slight.

-283-

A grave danger to the crew may be presented by contaminated air finding its way into the cabin. If we can in some way preclude the possibility of air entering the cabin, the effect on the crew is then only determined by the outside gamma radiation.

When an aircraft flies through the cloud, its external surfaces, engine and certain other parts into which air may find its way become contaminated. The radiation from a contaminated aircraft acts on the crew for the whole period of the flight, once the aircraft has passed through the cloud. A contaminated aircraft is no danger to the crew from the point of view of irradiation during subsequent flights, but precautionary measures are required when working on the aircraft, particularly the engine.

It should be kept in mind, of course, that the greater the speed of the flight, the less time the aircraft stays in the cloud and the less the irradiation dose.

3. Radioactive contamination during thermonuclear explosion

Radioactive contamination of a locality during a thermonuclear explosion is conditioned by the following two factors:

a) artificial (induced) radioactivity in the soil elements;

b) the fallout of radioactive matter from the cloud.

In the case of a thermonuclear explosion we can expect greater artificial radioactivity in the vicinity of the explosion, since the number of neutrons per unit area of ground is greater in this case. If the explosion occurs at a high altitude, the fallout of radioactive material is insignificant, since the bulk of it is scattered through the atmosphere. A certain amount of radioactive dust and ash thrown up into the atmosphere by the explosion may spread round the globe on account of the general circulation of the atmosphere.

If the thermonuclear explosions occurs at a low altitude, we observe strong contamination both in the vicinity of the explosion as well as along the trail of the cloud. During the hydrogen bomb tests carried out by the USA on
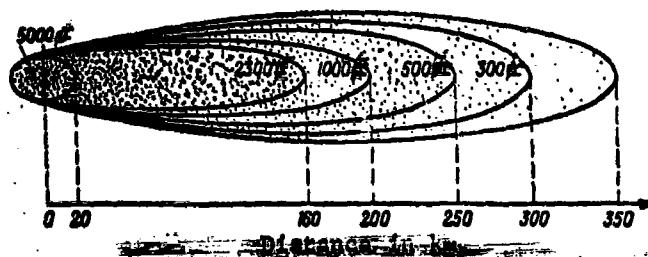
-284-

Fig. 85. Diagram showing radioactive contamination in the vicinity of the groundlevel thermonuclear explosion on March 1, 1954.

March 1, 1954, at Einiwetok Atoll (Pacific Ocean), the fallout of radioactive matter contaminated an area of the "trail" in the form of an elongated elipse, as shown in Fig. 85. The strip of fallout stretched 350 km in the direction of the wind and 30 km in the opposite direction. The drawing shows the radiation doses which could have been received by spending 36 hours in the contaminated zone, on condition the persons concerned were on open terrain and took absolutely no PROTECTIVE measures. The dose created during the 36 hours following the fallout of radioactive matter may be 2000 - 2300 roentgens at a distance of 160 km, and 1000 roentgens at a distance of 200 - 220 km from the point of the explosion. At the widest point the strip was approximately 65 km. Naturally, the data would have been different under other weather conditions.

At the moment of explosion on March 1, 1954, there was a Japanese fishing boat called the "Fukurui Maru" ("Lucky Dragon") about 140 km from the site of the test. At 3 am the fishermen saw a brownish-white flash of light on the horizon, and 7 - 8 minutes later they heard the sound of the explosion. The sky which had been completely clear up to that moment became covered with clouds. Several hours later the expanding cloud from the explosion reached the fishermen. The surface of the water and the deck of the boat became covered with an apparently harmless fine white dust which looked like ash.

The calcium carbonate which is the chief component of the coral of the island had been turned into calcium oxide by the high temperature. During the ascent and subsequent cooling particles of calcium carbonate were formed once more;

-285-

the diameter ranged from 0.025 to 0.5 mm. The dust *BEGAN* *TO SETTLE* the fishing
vessel began 3 hours and 30 minutes after the explosion, and *CONTINUED* for 4 hours.

The Japanese fishermen calmly went on fishing and had no idea of the *IMMINENT*
danger. They could not have known what the fallout of dust involved or what effect
it could have. It came to light later that the dust was radioactive and all the
members of the crew were contaminated.

Three days later they showed trauma of the integuments and symptons of
radiation sickness began to develop. The stricken fishermen did not return to port
until *M*arch 14, 1954, and it was only then that they received medical aid. One of
the victims, Leikitsi Kuboyama, died, while the others *HAD TO* *undergo* a long period of
treatment. Japanese physisists made a thorough examination of other fishing boats
returning from the fishing regions in the Pacific. One boat, which had been cruising
1500 km from Bikini on March 1, showed abnormally high radioactivity after its
return on March 31, 1954. Another boat which had passed Bikini at a distance of
about 800 km on April 16, 1954, also proved to be highly contaminated.

When the analyzed the radioactive dust which fell on the "Fukurui Maru"
after the explosion on March 1, Japanese scientists discovered a considerable amount
of uranium 237. This isotope is formed through absorption of one superfast neutron
by the uranium 238 nucleus and subsequent emission of two neutrons. During fission
there are extremely few neutrons with very high energy released, whereas during a
thermonuclear reaction they are present in large quantities. On the basis of this,
as well as consideration of the extent of contaminated area,
scientists concluded that *A* hydrogen-uranium bomb (thermonuclear charge with a
uranium shell) had been exploded. The US hydrogen bomb tests caused unrest through-
out Japan, since some of the fish *CAUGHT* off the Japanese coast proved to be contaminated.
Thousands of tons of fish were thrown back into the sea after a check. The
righteous indignation of the Japanese people was supported by millions of ordinary
citizens. The campaign for the banning of hydrogen weapons, as well as all other
means of mass destruction, was joined by the masses of populations of the whole
world.

Cobalt bomb. If we make the casing of the hydrogen bomb with chemical elements in which the neutrons produce radioactive isotopes emitting gamma rays and beta particles, we can step up the amount of radioactive matter formed during an explosion. The half-life of these elements may be several months or even several years. The foreign press has contained many references to the fact that cobalt as one of the most likely elements for a special bomb aimed at long periods of contamination of a locality. Cobalt has one stable isotope Co^{59}. When a Co^{59} nucleus captures a neutron, it turns into the radioactive isotope Co^{60} which has a half-life of 5 years and emits gamma rays and beta particles (low energy). Apart from cobalt, use can be made of zinc, (Zn^{65} has a half-life T = 250 days), Cesium (Cs^{134}, T = 2 years) and some other elements which have good neutron capture ability.

Thus, the cobalt bomb is not a new type of weapon in principle. It is a hydrogen, uranium or plutonium bomb, the radioactive action of which is intensified the use of specially selected elements.

Let us consider briefly the military possibilities of the cobalt bomb.

Supposing a hydrogen charge approximately 12 kg is surrounded by a cobalt shell in such a way that all the neutrons are captured by the atomic nuclei in the shell, then the total induced activity will be more than a billion curies. But a large amount of radioactive cobalt is only formed if the slow neutrons react with it. A nuclear explosion usually produces fast and superfast neutrons which slow down as they pass through the shell and are partially captured by the cobalt.

During the capture of superfast neutrons obtained, let us say, in the reaction between deuterium and tritium, the atomic nuclei of radioactive manganese (and not cobalt) are formed, and have a half-life of 2.6 hours. It must also be taken into account that during the explosion of a cobalt bomb fission products are also formed from the atomic detonator. If a bomb of this kind explodes in the air, there can be no great contamination. At the first moment the contamination would be approximately the same as for a bomb without a cobalt shell. The radioactive

cobalt falling onto the locality increases the DURATION of the contamination. In certain cases it could prevent a long stay in the locality, even at a small concentration.

In a zinc shell the activity is dozens of times less, and in a steel shell tens of thousands of timess less than for cobalt.

4. Effect of meteorological conditions on degree of contamination

The degree of contamination of a locality if affected by the meteorological conditions: wind, rain, snow and cloud.

If the wind is strong, the cloud containing radioactive matter is blown a long way from the point of the explosion and the radioactive dust falling from it is spread over a wide area. In the process the size of the contaminated area, particularly its length, is increased, while the degree of contamination is reduced.

The direction and speed of the wind in the layers of atmosphere near the ground are influenced by the topography of the terrain and the vegetation. The

the relief, the more complex the motion of the air, and this fact in turn causes uneven contamination of certain areas. When the air masses move around elevations and hills, more intensive fallout and therefore more intensive contamination are observed on the windward side. The leeward slopes are less contaminated.

Ravines, gulches, various kinds of cavities and indentations have a great effect on the spread of radioactive matter by the wind over the locality. If the wind blows along a ravine, contamination at the bottom of it is higher than when the wind blows across it.

Apart from wind, we have to take into account the vertical movement of air masses, which is mainly governed by the temperature distribution in the air above the ground. Hot air surges upwards, and the hotter the air, the faster it rises. Cold air comes down from the upper layers to replace the hot air, the movement of the air is thereby intensified, and rticles of dust take longer to fall out. It

-288-

is important to understand how terrain covered with forest becomes contaminated. One would expect less contamination in a forest at the moment of fallout than on open terrain.

The opposite effect occurs, however, and is manifested after rainfall. Movement through a contaminated forest increases the danger of contamination on account of contact with branches on which radioactive dust (or drops of water) have settled.

In winter a snowfall helps the radioactive matter to fallout of the cloud more rapidly, and the degree of contamination is increased, while the contamination of the air, conversely, is reduced.

Continued snowfalls result in the radiation emitted by the radioactive matter being weakened by the layer of snow, but, what is more important, the danger of people becoming contaminated when moving over the terrain is reduced.

Clouds during an atomic explosion may be one of the reasons for a fall of radioactive rain. In this case, as also in the case when the explosion occurs during rain, the radioactive matter falls onto the terrain together with little drops of water. There is more intensive contamination of the area over which the radioactive shower occurs.

A fall of radioactive rain may be explained by the factors as determine an ordinary rainfall.

An atomic explosion causes large masses of air containing water vapor to be drawn upwards. Consequently, as the atomic cloud rises, the flow of moisture into the upper layers of the atmosphere is increased. Furthermore, the solid particles in the cloud intensify the condensation of water vapor. Fine drops settle on these particles with radioactive matter in them and may later fall in the form of rain.

Investigation shows that in the troposphere there are usually enough condensation nuclei to produce clouds. An increase in the number of condensation nuclei may lead to water vapor condensing more intensively and   smaller drops

-289-

being produced. This may speed up cloud formation to some extent, but slows down the precipitation, since the fine drops cannot fall to earth.

In the stratosphere conditions may be slightly different. Here there is sometimes a deficiency of natural condensation nuclei, hence the addition of radioactive explosion products may promote cloud formation. But the amount of water vapor in the stratosphere is very small, so the clouds formed cannot produce precipitation.

A shower of radioactive rain is more likely in a case in which the atomic cloud passes through the rain cloud, and as it were, becomes part of it. The heaviness of the rain and the size of the region where it falls depend on the over-all meteorological situation and on the explosion conditions. An explosion above water during extensive clouds usually is accompanied by rain. For example, during the aerial explosion at Bikini in the Pacific there was light rain for 2 or 3 hours after the explosion above the island. The main reason for the rain was the presence of rain clouds at a low altitude. The rain covered a large area, but there was only radioactive rain in the area over which the atomic cloud passed.

5. Destructive effect of radioactive material

In a contaminated locality nuclear radiation may effect the human body in two different ways: an effect without the direct contact with the radioactive material (external irradiation) and the effect of radiation from radioactive material coming in contact with the skin, mucous membrane or finding its way into the body.

Radiation emitted by an external source may only damage the organism if it possesses sufficient penetrating power. Consequently, external radiation is determined basically by the effect of gamma radiation. Just as for gamma radiation from penetrating RADiation, this irradiation can cause radiation sickness, which has been described earlier.

But as distinct from penetrating radiation, which only lasts for a few seconds, gamma rays on contaminated territory may act on the organism for a con- siderably longer period of time.

When radioactive material comes in contact with skin, the alpha particles cannot enter the living tissue further than the surface layer; although the beta particles have a longer path, they cannot go further than a few milimeters. The effect of gamma rays is approximately the same as in external radiation. Radioactive material coming into contact with the skin in a fairly large amount, particularly the mucuous membranes of the eyes, the nose and mouth, may cause inflammation and sores.

Radioactive material gets inside the body more often than not together with the air; this is particularly likely when moving along dusty, contaminated roads when there is a strong wind. Radioactive matter may also be introduced into the body on food, water or by contact with contaminated objects.

What happens to radioactive material entering the human body? The material which by virtue of its chemical properties can form compounds is rapidly absorbed by the organism and carried round the whole body in the blood. HAVING / ENTERED the lungs or oesophagus, it can be detected in the blood within a few minutes. The undissolved particles stay in the lungs in different ways, according to their size.

When yttrium, zirconium, lanthanum, cerium and rufinium get into the lungs, they are transferred to the organism without difficulty. The lighter particles of the heavy elements plutonium, uranium, radium and so on, stay in the lungs for a longer time. When entering the body through the alimentary canal, elements forming soluble chemical compounds are absorbed very quickly.

When the enter the organism, the radioactive materials are carried round the whole body and in accordance with their chemical properties are retained by certain organs. Some radioactive materials are isotopes of elements contained in the protoplasm and in elements which take part in the metabolism (phosphorus, iodine, sodium, carbon and so on). The radioactive substances which are not isotopes of elements present in the organism, but are close to them in chemical properties, either displace or replace the allied element.

Many radioactive elements possess the power of selective accumulation in

certain organs or cells, creating a high ionization density. Iodine, for example, accumulates in the thyroid gland, while yttrium, plutonium, zirconium, strontium and barium usually accumulate in the bones, promethium, cerium and prasodymium gather in the liver, and so on. The degree of injury depends on the amount of radioactive material injuring the organism, the type and energy of the radiation, the distribution of the material through the organism, the half-life period and the time within which the material is excreted, and on some other factors. On this account the calculation of the dose of internal irradiation by atomic explosion products or any other mixture of radioactive isotopes is extremely complicated.

Such elements as Ru^{103}, Ru^{106}, Xe^{133} and Cs^{137} are excreted fairly soon from the organism, much more quickly than by natural decay. In the case of the short-lived isotopes, of course, natural decay plays the main part.

Long-lived isotopes constitute the greatest danger among the fission products. The list is headed by strontium 90, the half-life of which is 28 years. Strontium is close in its chemical properties to the very common element, calcium. In the human body strontium behaves in more or less the same way as calcium and may replace it. Just like calcium, strontium is carried round the body and concentrates in the bones, most of it in the vertebrae. Beta radiation from strontium may cause the development of malignant tumors in bony tissue.

Strontium may get into the human body by indirect means. It may first be absorbed by vegetation, subsequently consumed by livestock in the vegetation and finally consumed by human beings.

The International Commission for Protection from Radioactive Radiation has fixed the maximum permissible amount of strontium 90 in the human skeleton as 1000 micro microcuries per gram of calcium [1]. When it is considered that their calcium makes up 1.4% of the total weight of the human body, we find that the maximum permissible amount of strontium in the body is 1 microcurie. This amount of pure active material weights far less than 1 mg.

[1] The British Medical Research Council had determined this amount as 100 micro-microcuries per gram of calcium.

The harmful effect of radioactive matter inside the human body, even in small quantities, has been known for a long time. For example, in the twenties, several cases of radioactive poisoning were known in the USA among workers employed to ·PAINT luminous ᶠᴵᴳᵁᴿᴱˢ/ᴼᴺ clock dials.

Radioactive material entering the human body may cause radiation sickness through prolonged action and the gradual accumulation of the changes it brings about.

Radiation sickness caused by internal irradiation is marked by several specific features. At points through which the radioactive material passes or is secreted, as well as in the organs and tissues where it is deposited to the greatest extent, we observe a large number of inflammatory areas and sores. There is often inflammation of the lungs, especially when radioactive material is inhaled together with air.

Continual tests with atomic and thermonuclear explosives bring about an increase in the danger created by long-lived radioactive matter moving about all over the globe.

When an ordinary atomic bomb is exploded, the following isotopes have a prolonged radioactive effect: strontium 90, cesium 137 and carbon 14, the latter being produced when the nitrogen in the air captures neutrons. If a clean hydrogen bomb (deuterium and tritium) is exploded, the products with prolonged radioactive effect are carbon 14 and tritium.

The radiation doses produced by radioactive precipitations falling all over the world are very small. But the biological problems involved relate for the moment to the least studied aspect of radiation injury - chronically small effects. When radioactive material is taken into the human body, the stipulation is such that the irradiation should not exceed the permissible norm both in the human body as a whole as well as in the organ where the irradiation is greatest (this is ·called the critical organ). Calculations show that if atomic bombs with an overall TNT equivalent of

11 megatons are exploded every year, by the end of a century the concentration of
Sr in the critical organ (vertebrae) may exceed the permissible norm in large
groups of populations, and this may lead in a number of cases to congenital ailments
and serious blood diseases.

CHAPTER VII

ANTI-ATOMIC DEFENSE FOR TROOPS

1. Fundamentals of anti-atomic defense

Anti-atomic defense for troops consists of a series of precautions aimed at disrupting an enemy atomic attack, providing protection for the troops and ensuring their fighting fit ness in conditions in which nuclear weapons are being used.

Anti-atomic defense includes discovering the enemy's atomic preparations and thwarting the forthcoming atomic attack; warning troops of the danger of an atomic attack; deploying and camouflaging troops; supplying engineering equipment to positions and areas in which divisions are located and utilizing the natural protection of the terrain; continuous radiation MONITORING and the observance of measures for protection against radioactive contamination and, finally, liquidation of the aftermath of an atomic attack.

The most effective anti-atomic defense measures are the discovery and disruption of the preparations by the enemy for an atomic attack. The aim of these measures is to learn the presence and concentration of means of an atomic attack by the enemy (guided missiles, rockets, atomic artillery) and destroy them in good time.

A system of warning of the impending attack must be organized so that troops can take timely measures to ward off the atomic blow OR protect themselves from its injurious effect/ IF IT OCCURS. The warning is given when there is a direct danger of an atomic attack and is CONVEYED by means of visual and aural signal systems.

The enemy will use nuclear bombs, generally speaking, in a surprise attack. This follows from the fact that an attack of this kind is always prepared with greater secrecy and can be carried out with a small number of nuclear weapon carriers. Furthermore, the suddenness of an atomic attack is made possible by the use of long-range rockets.
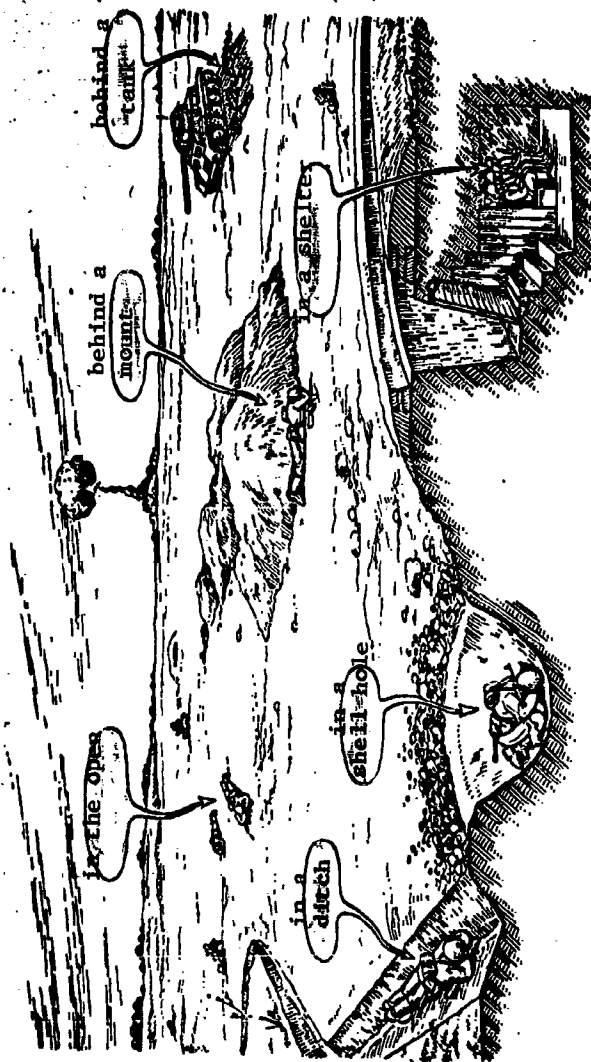
Fig. 85a.   As soon a the atomic flash has been seen, it is essential to take shelter immediately.

The duration of the destructive factors of an atomic explosion is incomparably greater than when conventional explosives are used. And since the overall damage done to an unprotected human being is determined by the total effect of the explosion over the total period of action of the destructive factors, having once seen the flash of the atomic explosion, it is still possible to be protected from it by swift action.

An atomic attack by the enemy cannot be a basis for ending hostilities. Having heard or seen the atomic raid warning, troops must have their personal anti-gas equipment ready, and then continue their particular mission. They must be attentive and maintain calm, discipline and organization; the commanding officer will show them what they are to do.

IN PROGRESS

If there is no actual fighting (when the signal is given, troops must take measures to protect themselves and their weapons *AGAINST* damage *By* the nuclear blast. Artillery, tanks, automatic gun emplacements and vehicles must be moved into shelters and troops must move into ready-made dugouts or shelters (Fig. 85a). The last one in should shut the door behind him and cover over the entrance with a screen. Chimneys and air vents in the shelters should be covered over.

If there are no shelters nearby when the atomic alarm is sounded, any fold in the terrain or local feature should be used as shelter, as shown in Fig. 82a. Rifles, instruments and radio receiving sets must not be left unprotected - they should be taken into the shelter as well; inflammable parts of equipment left outside should be covered with canvas or some other kind of covering as protection against the luminous radiation. Movement of troops is not halted when the alarm signal is given. Drivers should close windows (hatchways, blinds) and stay in place in the column.

Is it possible as a whole to protect oneself from a nuclear explosion, having seen the flash? Yes, it is, and in order to do so we must know the combat characteristics of the nuclear weapons, first and foremost the destructive factors. In order to select reliable methods for protection against atomic attack

we must know which of the destructive factors is the principal one, how long it lasts and at what speed it spreads through the air. This will enable us to find the right kind of shelter for personnel and to take protective measures against the atomic or hydrogen explosion.

It should be recalled that the principal factor causing destruction in a nuclear explosion is the shockwave. Although this wave spreads at supersonic velocity, it can only cover distances of 1, 2 and 3 km in 2, 5 and 8 seconds, respectively. The force of its effect on objectives located at this distance lasts for about 1 second. Luminous radiation is propagated at a very high velocity. So all unprotected objects are subjected to its action immediately after the explosion, ~~for~~ two or three seconds. Gamma rays - the basic component of penetrating radiation - also has an effect immediately after the explosion, but last for about 10 seconds.

By knowing these properties of the destructive factors, we can select and recommend defense measures for persons who are unsheltered at the moment of explosion. Let us consider an example of this.

Let us suppose that at the moment of an aerial explosion of an intermediate caliber bomb there is a man 2 km away from the point of explosion (Fig. 86). Let us consider the effect of the destructive factors on this person. Along the horizontal axis we will plot the time t (in seconds) from the moment of explosion. Since gamma rays and luminous radiation move through the air at a velocity of about 300,000 km/sec, an unprotected person 2 km away experiences the action of luminous radiation for 3 seconds immediately after the explosion and gamma rays for 10 seconds following it. Hence in 3 seconds the unprotected person receives all the energy of the incident luminous radiation and in 10 seconds the total irradiation dose.

The shockwave, the principal destructive factor, arrives at this point (2 km away) 5 seconds after the explosion. This is a very important fact, for it provides us with the rule which is recommended to follow in a nuclear explosion;
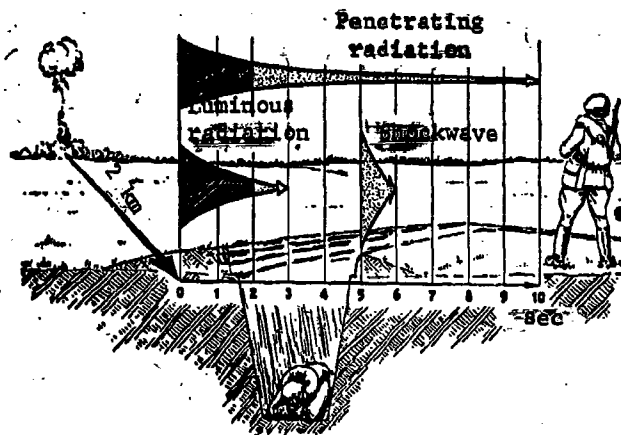
-297-

Fig. 86.   Graph showing effect of harmful factors
of atomic explosion in air on humans

having seen the flash, we must immediately take shelter (within 1 or 2 seconds) in a slit trench, crater, or shell hole). In this case the dose of gamma radiation, the luminous radiation energy and the shockwave load experienced by the person are greatly reduced. In Fig. 86 this is shown by the shaded area representing the effect of a nuclear explosion. If there is no shelter nearby, it is best to simply lie face downwards, keeping the hands under the body.

In order to disguise the DISLOCATION of troops, make it harder for the enemy to carry out aerial or ground reconnaisance and to reduce losses in the event of an atomic attack, we resort to deployment and camouflaging. Camouflaging is attained by skillful use of the terrain, activity at night and poor weather, the use of official and improvised means of camouflage and smoke screens.

Furthermore, the use of smoke for purposes of camouflage also weakens the effect of the luminous radiation.

As is known, the effect of the sun's rays on a misty or cloudy day is considerably weakened on account of scatter and absorption of the solar radiation by opaque atmosphere. So if there is a layer of cloud or mist between the point of an explosion of an atomic or hydrogen bomb and a particular target, the thermal effect of the nuclear explosion is obviously reduced. The damaging radii for luminous radiation are considerably reduced in thick mist. For example, if a nuclear bomb with a TNT equivalent of 20,000 tons is exploded on a bright sunny day, people in the open may receive first-degree burns as much as 2000 m away. But if there is a thick mist when the bomb bursts above the target, the damaging radius is reduced from 2000 m to 700 m. This gives rise to the problem of creating artificial mist or smoke screens able to reduce the effect of the luminous radiation. In this case the thick smoke formed when liquid or solid fuel is incompletely burned can be used to make a smoke screen. A smoke screen of this kind several tens of meters high (and of the same density as thick mist) may reduce the damaging radius of the luminous radiation by 2 or 3 times. Smoke screens may be used to reduce the damaging effect on troops on points where they are concentrated, to reduce areas of conflagration in populated points, naval

bases and forest land. Fig. 87 shows the areas of destruction due to luminous radiation during the explosion of an atomic bomb with a TNT equivalent of 20,000 tons; a circle with a radius of 4000 m is the limit of destruction on a clear day, and a circle with a radius of 1500 m is the destruction when a smokescreen is used.

Among methods of producing a smoke screen, are smoke bombs and special smoke machines and devices. Artificial mist can be made by means of a water spray from special equipment.

When making a smoke screen it is important to take into account the weather in the vicinity of the defended objective, the temperature of the air, the wind, the presence or absence of atmospheric precipitations which determine to a large extent the height to which the screen rises. Under certain circumstances it may happen that the cloud rises higher than the point of explosion of the bomb. In this case the light rays are reflected from the cloud and this in turn increases the destructive effect of the luminous radiation.

Smoke screens above great areas, apart from weakening the effect of the luminous radiation, afford camouflage for the deployment and maneuvers of troops and also hamper pinpoint atomic bombing. But in a number of cases it may be inadvisable to cover wide areas with smoke for a long time since it hampers the activity of the troops themselves.
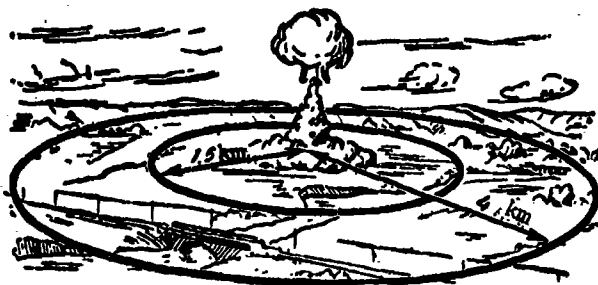

Fig. 87. Limits of destruction areas for luminous radiation on a clear day (4 km) and when using smoke screens (1.5 km).

Camouflage occupies an important place when atomic weapons are used. Solid, fireproof coverings can be used for this purpose. To increase their resistance to the effect of the shockwave, they should be strengthened with outside and inside braces. To increase the resistance of camouflage coverings to luminous radiation use can be made of metal netting with intertwined metal shavings, atmosphere-resistance paper or cloth treated with a fireproof composition. Camouflage coverings from improvised materials (reed, dry wood, straw, etc.), should be impregnated or smeared over with a clay solution.

In order to reduce sharply or even completely eliminate the effect of a nuclear explosion on personnel, armaments, buildings and equipment, positions and areas of deployment of troops have to be fortified by utilizing the protective features of the terrain. Anti-atomic fortification of a terrain consists in strengthening and adapting the terrain for hostilities. Radiation reconnaisance is employed to detect radioactive material in good time, to determine the radiation level, to mark the contaminated areas of a locality, to seek out the waste and to warn troops of the danger of contamination.

Radiation reconnaisance is carried out in all units and subdivisions the whole time during any kind of fighting.

In order to restore the fighting fitness of troops after an atomic attack, the aftermath of the latter has to be liquidated. This operation includes: rescue work, repairing of equipment, extinguishing fires, restoring destroyed or damaged defense installations, communication lines, first aid for human beings and veterinary treatment for animals, as well as decontamination of equipment, weapons, and food products.

2. Individual and group defense measures

Under conditions in which the use of nuclear weapons is possible, individual and group methods of protection acquire particular importance.

Group methods include the covering over of trenches, passage ways, dugouts, special shelters, various underground excavations and tunnels.

Trenches and communicating passageways are the basic method of fortifying
a locality. They are dug at the initial position for an advance, during defense,
and during the fortification of important lines while hostilities are going on.
Trenches and passageways are essential for maneuvering troops and equipment,
and for engaging the enemy, apart from providing protection from bullets, schrapnel,
the effect of the shockwave, penetrating radiation and luminous radiation.

In order to improve the protection afforded by trenches and passageways,
they should be dug to a depth of 1.5 - 1.8 m and covered over on top. The coverings
are made of poles, logs, or beams LAID tightly together across the trench
directly on top of the soil and then covered with a layer of earth up to 50 cm
thick. If the soil is loose, the walls of the trench are strengthened with planks,
poles, slabs or reeds. Ramparts and rear passageways are dug out in the trenches.
When viewed from above, the trenches and passageways should not be run in straight
lines, but in zig-zags though without sharp corners.
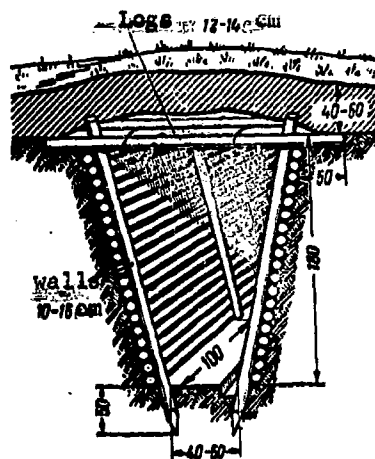
Fig. 88. Trench with covered top and walls.

During a nuclear explosion, it is possible that the materials from which
the fortifications are made may catch fire. Hence, the lining of the trenches
and passageways as well as in other shelters should be coated with soil or clay,
and with lime in winter. Every 20 or 30 m there should be gaps in the walls 2 m

wide for firefighting equipment. A covered trench with lined walls is shown in Fig. 88.

The uncovered areas of the trenches contain observation points, machine gun emplacements, and niches for ammunition, food and water.

Niches or dugouts (Fig. 89) are often built under the ramparts near machine gun positions. If the soil is loose, the walls of the NICHES are strengthened with poles, planks or slabs. The entrance to the niche has a covering made of planks.

Fig. 89. Niche below rampart.

The most reliable cover for personnel is the shelter (Fig. 90). It can be either the lighter or heavier type and is made of wood or ferroconcrete. In certain cases shelters can be built with corrugated steel.

Heavy-type shelters protect personnel from injury by an atomic explosion when they are inside the area of the epicenter of an aerial explosion. The shelters possess these protective properties since they are strongly built and can withstand large loads. Protection from the penetrating radiation and luminous radiation, just as from shells and bombs, is afforded by a sturdy covering and a very thick layer of earth.

Shelters are constructed by mechanized methods with pre-prepared parts and structures. People in the shelters do not need to take personal protective

measures since the shelter contains filtering and ventillation equipment. The
air intakes are fitted with special anti-explosion valves, which prevents the
shockwave penetrating inside. In extreme cases the exhaust, intake and other
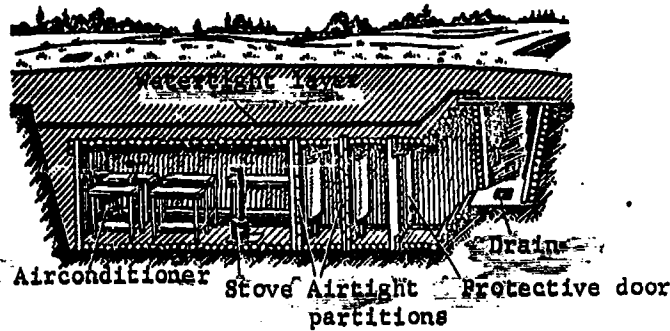orifices are fitted with airtight covers which are closed by hand.

Fig. 90. Lighter type of shelter.

Shelters have two exits - a principal exit with an airlock with a
protective door and an airtight partition, and an emergency exit in the form of
a shaft. The entrance to the shelter has to be made airtight to prevent radio-
active material getting inside the shelter.

Group anti-atomic defense measures sharply cut down the radius of de-
struction from atomic weapons. The stronger the construction, the more reliably
it protects people from the explosion. The simplest fortifications reduce the
destruction radius by a factor of 1-1/2 or 2, and the stronger constructions
reduce it by a factor of 3 or more.

Aboard ship superstructures, gun turrets and armor plating are used for
protection from the explosion. If there is no shelter nearby, nor any fold in
the terrain, persons should lie flat on the ground (deck) face down. By lying
in this way it is possible to avoid the injury from the shockwave or to reduce it
to a consideable extent and to save the face from burns. The hands should be
hidden under the body and the eyes closed to prevent temporary loss of vision.
Soldiers inside tanks during the flash from an atomic explosion should shut all

-303-

the hatchways and peepholes, as indicated above; persons inside cars should duck
down below the level of the windshield to avoid injury from flying glass and the
luminous radiation; persons in the back of a truck should lie on the floor, and
if this is not possible, they should crouch down. In the gun turret of a ship,
when the flash has been seen the gunners should duck down immediately to avoid
being burnt by the luminous radiation.

The destructive range of an atomic explosion can be considerably reduced
as a whole by sheltering the personnel, and, as shown in Fig. 91, the stronger the
construction, the better the protection it affords. If we take it that the safe
distance for an unprotected person during an aerial explosion is R, persons
sheltering in completed, open trenches will be uninjured at 2/3 R. Trenches
covered with beams and with a 50 cm layer of earth halve the destructive range,
while dugouts reduce it by a factor of 3. Finally, persons sheltering in under-
ground, strong constructions more than 10 m deep will not experience any injury
at all even if the shelter is at the epicenter of an aerial nuclear explosion.
Clearly, shelters of this kind are adequate protection for all types of destructive
nuclear action.

Shelters for military vehicles, armaments and equipment can be of the
covered or uncovered type. For armaments - machine guns, mortars, guns and tanks
are usually of the uncovered type.

Emplacements for machine guns or artillery are guarded with a narrow,
wide or circular firing sector (Fig. 91a). For mortars the trenches are made
deeper.

The trenches dug for tanks and self-propelled artillery when they are
in position include firing platforms, shelter for the tanks and dugouts for the
crews (Fig. 91b).

In areas where troops are waiting to go into the attack and areas in which
they are concentrated, shelters containing dugouts for the crew are constructed
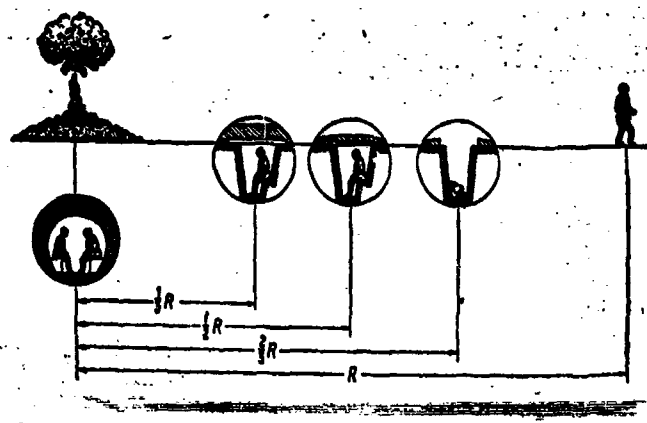for tanks. Basin-type shelters with a RAMP   for entry and dugouts for the

-304-
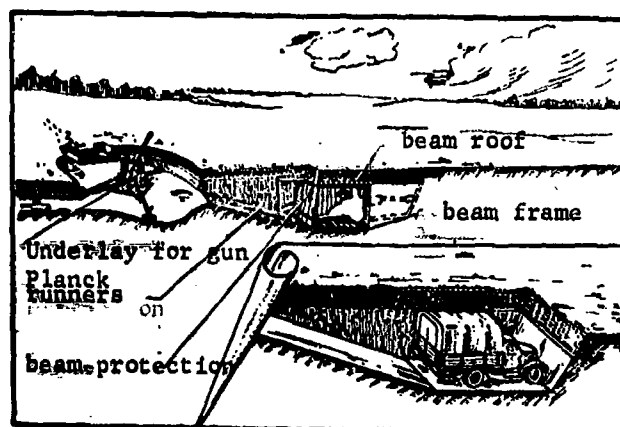
Fig. 91. Safe distances from atomic explosion

Fig. 91a. Trench for artillery and vehicle shelter
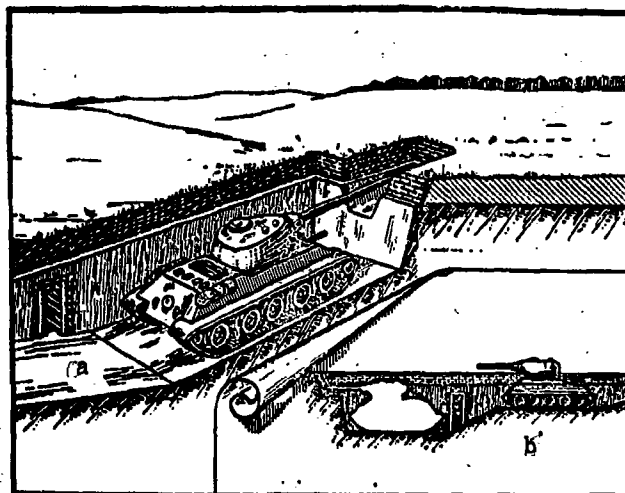for anti-atomic defense

Fig. 91b. Shelter (a) and trench (b) for tanks.
Entrance to a dugout for the crew can be seen
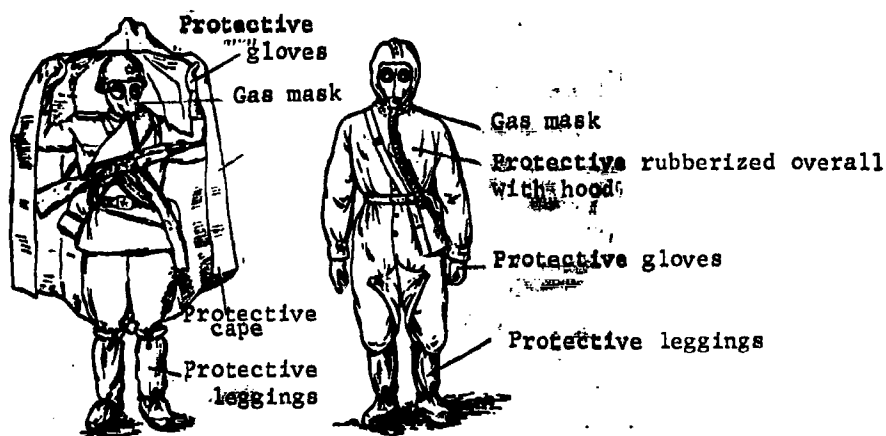in side wall.

Fig. 91c. Personal anti-gas equipment for soldiers (left)
and sailors (right).

drivers should be constructed for trucks and tractors (Fig. 91a). Different types of equipment are kept in basin-type shelters in the packed form.

Munitions are stored in crags, gulches or special shelters. Fuels and lubricants are stored in basin type shelters. Fuel containers should be buried in the ground and food and equipment is best kept in slit trenches. Personal means of protection are subdivided into issued and improvised equipment. The gas mask, protective suit, protective overalls, protective cape, protective gaiters and gloves comprise the issued equipment. Fig. 91c shows the personal protective equipment for soldiers and sailors.

Gas masks are divided into the isolating and filtering type. In isolating gas masks the oxygen is contained in a special cylinder and fed directly to the respiratory organs as required. Filtering gas masks purify contaminated air and afford complete protection from the entry of poisonous and radioactive matter into the body or onto the integuments of the face and head.

The anti-gas cape (or ground sheet) protective gaiters and gloves, protective overalls, and suit and apron prevent radioactive material getting onto the uniform, footwear, equipment and uncovered parts of the body.

If there is no issued equipment available, improvised equipment is used. A handkerchief, towel, wool or gauze, damped with water from a flask or uncontaminated water supply, can be used to prevent radioactive material getting into the respiratory organs. The protective gaiters can be replaced by sacking, bast or rags. When lying down on terrain, mats made from uncontaminated twigs, straw or reeds should be spread out underneath.

When the contaminated area has been captured, the gas mask and ground sheet are not taken off until the commanding officer says so. They have to be removed in a strictly laid down order. The soldier stands with his face to the wind and taking hold of the inside of the cape, quickly throws it off. After this he removes the gaiters, and then, still in the gas mask, carefully shakes the cape, gaiters and equipment. Last of all he takes off the gas mask and gloves.

-305-

The improvised protection is sent to the decontamination point, or if no longer needed, buried in the ground.

Issued equipment for anti-chemical protection is tested for radiation and decontaminated after use. Particular attention should be given to decontamination and dosimetric inspection of the gas mask since radioactive elements, a source of harmful radiation may accumulate in the filter with time.

3. Radiation reconnaisance and monitoring

Radiation reconnaisance. One of the characteristic features of the destructive effect of radioactive material is the impossibility of detecting the radiation without dosimetric instruments. This is because, as already mentioned, radioactive radiation does not cause any sensation when it acts on our organs of senses. Nor can the radioactive material emitting this radiation be detected, since, first, it has no specific properties (color, smell or taste) and, second, the amount of material, even in strong contamination, is a tiny fraction of a gram per square meter.

This feature of radioactive material means that is can have serious consequences if measures are not taken to detect it in good time. Hence one of the fundamental anti-atomic precautions for all branches of the forces is radiation reconnaisance coupled with monitoring. It should be stressed that detection of contaminated areas in good time and area and personal monitoring make it possible to avoid the loss of personnel operating in a contaminated locality.

Radiation reconnaisance is carried on the whole time, day and night, since the personnel may be subjected to irradiation unexpectedly and may have to operate in the contaminated locality for some time.

The purpose of radiation reconnaisance is:

1) to detect contaminated areas of the locality and to warn the relevant commanding officers in time;

2) to ascertain the extent of contamination of the areas and to mark the

boundaries with the appropriate warning signs;

3) to find methods of dealing with the contaminated area.

Fig. 92. Signs warning against radioactive contamination of areas:
a) official signs; b) improvised warnings when there are
no official signs available.

The degree of contamination of an area is usually assessed in terms of the
gamma radiation level (roentgen/hour) since this radiation presents the greatest
danger to personnel. The monitoring devices used to measure the radiation level
in roentgen/hour are termed r-meters. Apart from r-meters, very simple dosimetric
devices - radioactivity indicators - can be used to detect contamination.

Fig. 92 shows the official warning signs. The warning signs are usually
placed on the boundary of areas with radiation level 0.5 roentgen/hour. But, as
ordered by the commanding officer, they may be used to mark areas with higher
radiation levels.

When measuring the radiation level it has to be kept in mind that the level
depends on the time which has elapsed since the explosion as well as the height at
which the measurement is made, hence the time and date of measurement are always
indicated on the sign, while the actual measurement is taken at a height of 0.7 -
1 m. Fig. 93 shows the variation in the gamma radiation level with height above
a contaminated area. The radiation level at 0.7 - 1 m high is approximately half
way between the level on the ground and the level at the height of a human being;

-307-

this enables us to assess the effect of the radiation on the body as a whole with a fair degree of accuracy.

Local objects acting as shields also have a marked effect on the radiation level. In a trench the radiation level is lower than on open terrain since the walls of the trench appreciably weaken the radiation from radioactive material lying on open ground. Local objects such as lumps of earth, stones and different structures may also weaken the radiation level. All these facts should be taken into account when measuring it.

If there are no official signs available, contaminated areas are marked with improvised signs (Fig. 92b).

Radiation reconnaisance is carried out by a monitoring scout who is sent out to reconnoiter the area of operations of the troops or individual routes. The scouts usually operate in armored cars or trucks. If the radiation level is high or if the terrain is impassable, the reconnaisance may be carried out in tanks. Monitoring in trenches, passage ways and other fortifications can be done by scouts on foot. The monitoring of extensive areas and long highways can be conducted from aircraft (helicopters).

The scout uses r-meters for the monitoring operation. While in motion, one of the scouts keeps a continual check on the r-meter readings. On the boundary of areas with radiation level of 0.5 roentgen/hour he puts up a warning sign. A brief halt is made to measure the radiation, but the operation is carried out inside the vehicle.

When reconnoitering contaminated areas occupied by troops, the scout first measures the radiation level at the places where the troops are located.

Aerial reconnaisance of a locality is carried out with monitoring devices carried aboard the aircraft or helicopter by flying consecutively from one area to another in a given order.

On account of the considerable penetrating power of penetrating radiation in the air, MONITORING instruments aboard an aircraft enable us to detect areas

contaminated by gamma-active materials at heights appreciably greater than the minimum safe height for flights by aircraft (helicopters).

The maximum altitudes *AT WHICH* contaminated areas [*CAN BE DETECTED*] *are CONDITIONED BY* the flight altitudes at which the gamma radiation level becomes commensurate with the intensity of the cosmic radiation. Whereas the gamma radiation levels *FALL* with height fairly rapidly, the intensity of cosmic radiation, conversely, is appreciably stepped up with altitude. Hence, even if we use extremely sensitive instruments, the maximum possible heights for detection of very strong contamination foci are not greater than 1000 m.

It should be pointed out that . data such as the radiation level on the ground and the boundaries of contaminated areas can only be assessed very roughly by aerial reconnaisance. The thing is that an airborne dosimetric device measures the gamma radiation level at the height of the aircraft (helicopter) and not at the ground level. To assess the radiation level at the ground from the radiation level measured at a particular height, we must have data on the reduction in the radiation level with height, that is to say we have to know the attenuation factor of the radiation level as a function of the flight altitude.

But the attenuation factor depends both on the flight altitude as well as the size of the contaminated area, its shape, the nature of the contamination (uniform or non-uniform) and certain other factors. All these data, apart from the flight altitude, are unknown during aerial reconnaisance, and this may result in large errors in the attenuation factor. Particularly gross errors may be made in determining the radiation level by the ground if the linear dimensions of the contaminated area are less than the flight altitude. Hence to obtain reliable data on the "topography" of the contaminated locality, the flight altitude must be as low as possible.

The shortcomings of aerial radiation reconnaisance due to the difficulty of obtaining detailed data on the radiation at ground level are fully compensated

by the fact that the use of aircraft makes it possible to reconnoiter an extensive area in a short time.

This is a very positive feature of aerial reconnaisance and enables us to plan effeciently and greatly step up ground reconnaisance, as well as providing us with the opportunity of taking the necessary steps to protect troops in good time.

In a number of cases aerial reconnaisance is virtually the only way of discovering the radiation set-up. Other ways are reconnaisance of foci of very strong contamination (areas close to the centers of ground level and underground atomic explosions), reconnaisance of regions in the rear of the enemy abandoned when our troops advanced, and so on.

Monitoring. Monitoring is one of the measures applied to protect personnel from injury due to radioactive material. It is subdivided into external irradiation monitoring and internal radiation monitoring.

External radiation monitoring, is carried out to prevent personnel being irradiated above the allowable norm. The operation consists in measuring the radiation dose obtained by personnel when operating in a contaminated locality as well as when working on decontaminating contaminated equipment and weapons. External radiation monitoring in the field is conducted on the basis of gamma radiation doses. It should be pointed out that the principle protection methods (special capes, suits and so on), for protection from external gamma radiation is no good at all, since a layer of lead 0.7 cm thick only reduces the intensity of gamma radiation by a factor of 2. Hence, the chief precaution for persons operating in a contaminated locality is to keep to the time limits within which they may stay there. As soon as a man has received the permissible dose, he should be insulated from the effect of radioactive radiation. On account of the small penetrating power of beta radiation, the possibility of people being injured by external irradiation is considerably less than for gamma radiation. Indeed, beta radiation is almost totally absorbed by the sole of a pair of boots, by any metal screen a few milimeters thick, and a stream of beta particles at the level of the

man standing up is weakened by at least a factor of 10.

Irradiation monitoring is usually subdivided into individual and group monitoring.

Individual monitoring is carried out to ascertain the radiation dose received by each person during his stay in the contaminated area. . The monitoring devices used for this purpose are called personnel monitors. The monitor measures the total dose in roentgens.

Group monitoring is carried out in cases in which the personnel of a unit operate under more or less the same conditions and therefore all receive about the same radiation dose.

To measure the dose during group monitoring use is made of r-meters and personnel monitors.

When using an r-meter, it is placed in the area where the personnel is located at the point of greatest radiation level. The radiation dose in the case of a constant radiation level is determined from the equation $D = P \cdot t$, where P is the gamma radiation level, in roentgen/hours and t is the time spent by the people in question in the contaminated area in hours.

If the radiation level is variable (for example, when capturing a contaminated area with different levels), the mean radiation level is substituted into the equation.

When personnel monitors are used for group monitoring, they are issued to two or three soldiers. The readings are used to determine the mean radiation dose obtained by the personnel as a whole.

<u>Internal radiation monitoring</u> is carried out in order to prevent radioactive matter entering the human body or coming into/ $_{CONTACT\ WITH}$ uncovered parts of it. Internal radiation, as has already been pointed out, occurs in cases in which the radioactive material makes its way into the body through the swallowing or inhaling of contaminated dust, water or so on. It must be remembered that radioactive material spread over the surface of an object may be completely harmless from the

point of view of external irradiation, but dangerous if it comes into direct
contact with a human being and thereby has a chance of entering the organism.
Military equipment and other contaminated objects are therefore a danger when being
removed from the contaminated area, unless the appropriate precautions are taken.

Monitoring also includes measuring the degree of contamination of different
surfaces and volumes. In a contaminated location, the beta-active particles are
in practice the most dangerous form of radiation if they get inside the body. Hence
the degree of contamination is based on the beta-active material.

The unit of measurement of radioactive material, as is known, is the curie.
Consequently, the units used to measure the degree of contamination of a surface or
a volume ought to be, respectively,

Curie/cm^2, curie/liter, curie/cm^3 and so on.

But the curie is too large a unit for the amount of radioactive material.

Hence, to determine the degree of contamination of clothing, the surface
of the human body, the surfaces of military equipment, water, air and so on, the
amount of radioactive material is measured by the number of decays of the atoms
per minute (1 decay/min = $4.5 \cdot 10^{-13}$ curie). With this selection of units, the
degree of contamination of a surface is measured by the number of decays of atoms/
cm^3 min, and for fluids as decays of atoms/cm^3 min and so on.

The instruments used to measure the degree of contamination have come to
be called radiometers.

Monitoring is usually conducted after the personnel have left the con-
taminated zone, and also when carrying out full sanitary measures and decontam-
ination.

Contamination monitoring is carried out by chemist-scouts who determine the
degree of contamination of the entire personnel, armaments, equipment and the
effects. If the measurements show that the contamination is higher than the norm,
the personnel undergoes prophylactic treatment, and weapons, equipment and food
are decontaminated.

-312-
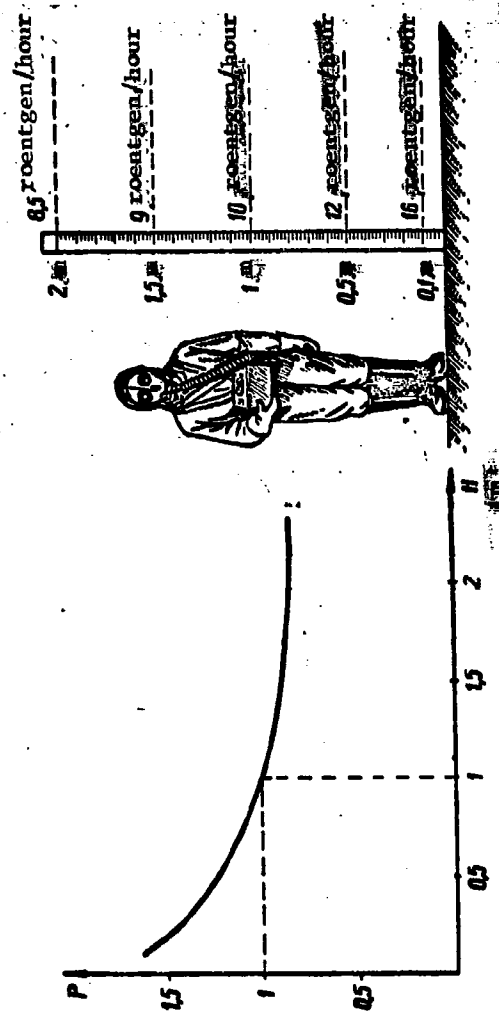
HEIGHT IN M ABOVE CONTAMINATED SURFACE

Fig. 93. Change in gamma-radiation level including height above level of contaminated terrain.

On the left: graph showing height (radiation level at height of 1 m is considered equal to 1).

On the right: radiation levels at different heights, if radiation level at 1 m is equal to 10 roentgen/hour.

4. Field monitors

Table 32 shows the basic types of monitors used to measure radiation in the field. The sensing unit in these monitors is the ionization chamber or gas counter. All monitors, except for indicators, are powered by batteries.

Let us consider the working principle and application of these monitors in detail.

General characteristics of field monitors

Table 32

No.	Type of monitor	Receiving device	Basic purpose of monitor	Measured quantity	Unit of measurement	Basic measurements
1	Radioactivity indicators	Gas-discharge counter	Detection of radioactivity	Radiation level	roentgen/ hour	Gamma-radiation
2	r-meter	Ionization chamber	Evaluation of contamination degree	Ditto	Ditto	Ditto
3	Radiation-monitor	Ditto	Monitoring of exterior irradiation	Irradiation dose	Roentgen	"
4	Radio-meter	Gas-discharge counter	Monitoring contamination of various surfaces, volumes	Contamination degree	Decay/ min.cm^2 Decay/ min.liter etc.	Beta-radiation

Radioactivity indicators. The radioactivity indicator is the simplest field monitor intended for detecting contamination of a locality by gauging the gamma radiation dosage rate. The monitor starts recording the gamma radiation when the latter is between 0.05 and 0.5 roentgen/hr. Furthermore, the monitor enables us to detect beta radiation.

The basic parts of the monitor are an STS-5 gas counter, a current generator for a hand electro-dynamic torch, two neon tubes, a voltage stabilizer tube (red) and a signal light (white).

The monitor is slung over the shoulder on a strap. Its weight is not more than 1 kg. Fig. 94 shows the outside of the monitor. There is a window with thin celluloid at the bottom of the casing to give the beta particles acess to the gas counter. When gamma radiation is recorded, the window is covered with

-313-

a metal shutter.

To switch on the indicator, the current generator is set in action by periodically squeezing the handle. Frequency with which the handle is squeezed is such that the voltage stabilizer light glows continually, showing that the monitor is working normally.
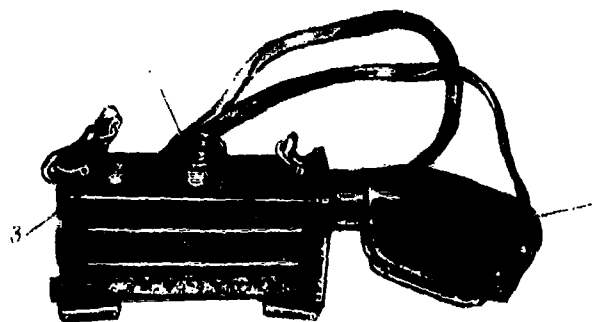

Fig. 94. External view of radioactivity indicator: 1) generator; 2) neon signal light; 3) neon stabilizing circuit light.

When gamma radiation acts on the counter, current pulses are produced in the circuit and charge up the storage condenser. The neon signal light is connected in parallel to the condenser. When the voltage in the condenser equals the potential required to ignite the neon light, the latter gives a flash and its resistance drops to a low value. This makes the condenser discharge rapidly and return to its initial position. The greater the intensity of the radiation, the more frequent the current pulses. As the frequency of the current pulses are increased, the charge-up time of the condenser decreases, leading to a decrease in the flashing frequency of the signal lamp. The parameters of the circuit are selected in such a way that separate periodic flashes occur when the radiation ranges from 0.05 to 0.5 roentgen/hr. If it is greater than 0.5 roentgen/hr, the frequency with which the lights flash is stepped up to such an extent that the separate flashes merge into one continuous glow.

To check for contamination of locality with beta-active material, the

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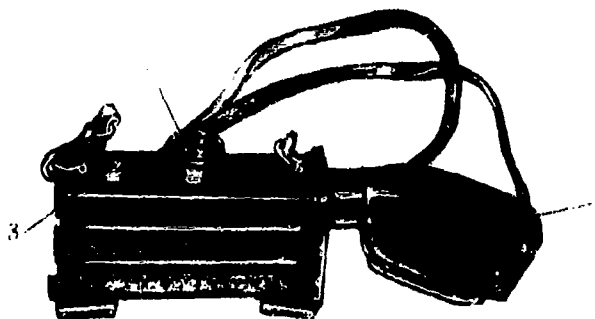

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To check for contamination of locality with beta-active material, the

shutters covering the window at the bottom of the casing have to be opened, and the monitor itself is brought close to the ground to a distance of 20 or 30 cm. Variation in the flashing frequency of the signal light with the window open and closed shows the presence of beta radiation. It must be kept in mind that when the window is open, the monitor is reacting to the total beta and gamma radiation intensities.

Field r-meter. The field r-meter is the chief instrument used for ground-level radiation reconnaisance. It is intended to measure gamma radiation levels ranging from 0.04 to 400 roentgen/hour. In addition to this, the instrument gives a rough indication of the beta radiation level. The measurement range is divided into four sub-ranges. Fig. 95 shows the instrument from the outside. It weighs about 6.7 kg and is serviced by one man who carries it on straps.

The instrument consists of a sensing device (ionization chamber), an electronic amplifier, a microammeter, with its scale fitted to the face of the instrument, and a power source (battery). All the parts are mounted in a metal casing. At the bottom (underneath the ionization chamber) there is a window covered by a metal shutter. This shutter is pulled back when measuring the beta radiation level. The chamber consists of an external electrode - a cylindrical plastic box acting as the body of the chamber - and an internal T-shaped electrode. A voltage of about 300 volts is applied to the chamber electrodes. The volume of the chamber is filled with air and hermetically sealed.

Unless there is radiation, there is no current in the electrode circuit, since the air filling the space between them is a good insulator. If ionization radiation occurs, ions are created in the air space, the positively charged ones moving towards the cathode (internal electrode) and the negative ones moving towards the anode (external electrode). The directional motion of the ions is the reason for the creation of a current in the chamber circuit. The magnitude of the current is proportional to the dose rate.

Between the internal electrodes and insulator there is a so-called guard ring which protects the electrode from insulator leakage currents. Leakage currents are always directed in the same direction as the ionization current and may lead to an inflated reading.
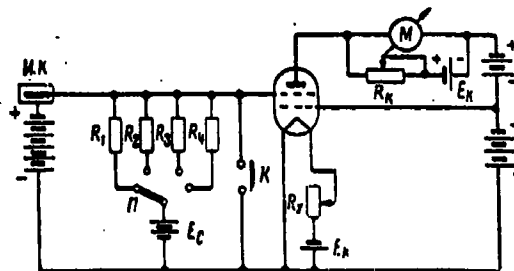

Fig. 96. Simplified r-meter circuit.

Since beta particles only have slight penetrating power, there is a window in the wall covered with thin aluminum foil.

Even when the radiation level is high, the ionization current is only billionths of an ampere, hence it must be preamplified if it is to be measured. For this purpose this cathode circuit contains a high-ohm load resistance, the voltage drop in which is fed to the amplifying tube grid. The anode circuit of the tube is connected to a microammeter with a scale graduated in roentgen/hour. Fig. 96 shows a simplified r-meter circuit. The replacement of sub-ranges is effected by stage-by-stage variation in the resistance of the load in the chamber circuit. At the first (most sensitive) sub-range, this resistance amounts to 47 $\cdot 10^9$ ohms, while at the next sub-ranges it is 10, 100 and 1000 times smaller, respectively. The switch-over from one resistance to another is carried out by means of the sub-range switch Π, the manual control for which is attached to the front panel. The contact K, which is also on the front panel, is used to test for a zero reading in the contaminated zone. When the button is depressed, the load resistance short-circuits and the ionization current does not cause any voltage drop in it.

To amplify the ionization current there is a special electronic tube which has come to be called an electrometric tube. Electrometric tubes have a number of characteristic features: 1) the anode voltage does not exceed 8 - 10 volts;

2) between the controlling grid and the cathode there is a so-called grid which helps to improve the amplifying power of the tube at low anode voltages;

3) a very large leakage resistance between electrodes (as much as $10^K \Omega$).

Like all field monitors, the field r-meter is intended for relative measurements, that is to say it may only be used after calibration. The isotope Co^{60} is usually used as the control gamma source. The method of calibration is simple. The gamma radiation level at certain differences for the given activity of the source can be determined from the equation

$$P = \frac{1,35Q}{R^2} \text{ roentgen/hour}$$

where Q is the activity of the source in curies, gauged on the day the calibration was carried out;

R is the distance from the source in meters.

During the calibration it is usual to check the correspondence between the instrument readings and the true radiation level at three points along the scale: at the beginning, in the middle and at the end of each sub-range. The distance from the source corresponding to the given radiation level P is found from the equation $R = \sqrt{(1.35 \text{ } Q/P)}$. The instrument is placed with its underneath towards the source in such a way that the distance between the source and the center of the chamber (the center of which is marked with a cross) is equal to R. If the instrument reading at the most sensitive sub-range does not correspond to the theoretical value P in the middle of the scale, the sensitivity of the instrument is adjusted. At the other sub-ranges there is only a check on the correspondence between the readings and the theoretical values of P.

-317-

Before carrying out measurements it is essential to test the filament voltage and the zero setting. The sequence to be applied in repairing the instrument is shown on the lid which covers the control panel.

To measure the radiation level the instrument is usually placed 0.7 - 0.1 m above the ground; as has already been mentioned, this height corresponds to the mean radiation level for a person standing on the ground. When approaching the contaminated area, the instrument is switched on to the most sensitive sub-range. If no radiation is recorded, the second sub-range is switched on and so on. In order to be able to replace the power supply in good time and thereby be certain that the r-meter will not conk out during operation, a calculation has to be made of the time during which the instrument is switched on.

When measuring gamma radiation levels, the duralumin shutter in the bottom of the casing should be opened so that the beta particles can enter the chamber without appreciable absorption. The difference in readings with the shutter open and closed, when multiplied by 10, gives the radiation level in roentgen/hour.

The instrument can also be used to find out whether or not the locality is contaminated with radioactive material at the point of measurement. To do this, we open the shutter in the bottom and bring the instrument close to the ground; if the terrain is contaminated, the readings become several times greater.

Personnel field monitor. This instrument is intended for monitoring the external gamma irradiation of personnel located in a contaminated locality. The instrument contains miniature ionization chambers and a charging-measuring panel (Fig. 97).

By means of the same ionization chambers the instrument makes it possible to measure doses from 0 to 5 roentgens (first sub-range) and from 0 to 50 roentgens (second sub-range). The weight of the separate chamber is about 15 g. The chamber is made in the shape of a fountain pen and carried in the pocket to make it easier to use.

The miniature ionization chamber consists of an aluminum cylinder (external electrode), with an aluminum rod (internal electrode) running along its axis. There
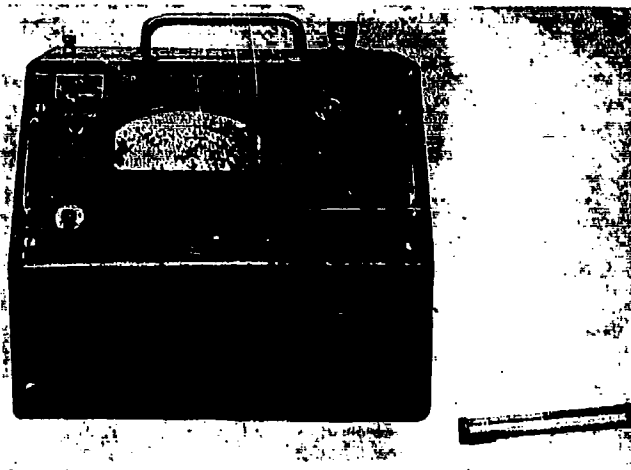
Fig. 97. Outside view of personnel monitor and charging-measuring panel.

is a condenser inside the chamber, one facing of which is connected to the cylinder, and the other to the aluminum rod. The chamber operates in the following way. The chamber condenser is charged to a certain voltage by means of the charge-measuring panel. When gamma radiation acts on the chamber, ions are formed in the working volume and as they move towards the electrodes, they create a current which reduces the condenser charge. This reduction in the charge and, therefore, the charge in the voltage, is proportional to the radiation dose at the site of the chamber. By measuring the voltage remaining in the chamber by means of the charge-measuring panel we can assess the dose. The scale of the electro-measuring device on the panel is graduated directly in roentgens.

The chamber condenser is subject to self-discharge as a result of inevitable leakage currents. It is therefore desirable to charge the chambers and issue them to the personnel just before entry into the contaminated area; these chambers have to be treated carefully. Moisture getting inside the chamber may cause increased self-discharge, so the chamber should be protected from moisture and rain
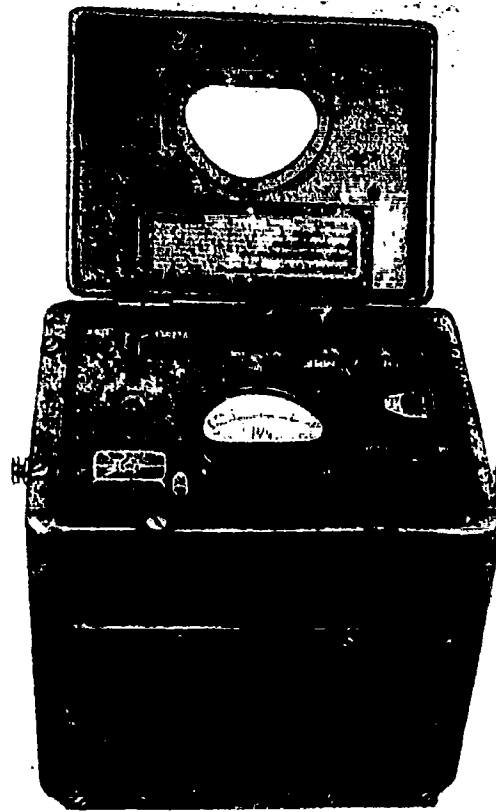
-319-

Fig. 98. Exterior view of field r-meter with open lid

as far as possible.

Field r-meter. The field r-meter is used to measure the degree of contamination of a different surface and the soil by beta and gamma-active material, as well as to gauge the degree of contamination of air, food and water. Furthermore the instrument can be used to measure low gamma radiation levels in miliroentgens per hour. The degree of contamination of surfaces is gauged by the number of decays per 1 cm^2 per minute. The range of measurement for beta contamination lies between 150 and 1 million decay/cm^2 min, and for gamma radiation between 0.03 and 20 miliroentgen/hour. The entire measurement range is split into two sub-ranges, controlled by a change-over switch on the control panel.

To prevent the instrument being damaged and to avoid large errors, it should not be used under conditions of high radiation intensity; the main purpose of the instrument is to check the contamination of different objects when leaving a contaminated locality.

The r-meter consists of two blocks (Fig. 98): a control panel and a probe. Telephonic earphones are also part of the equipment. The weight of the instrument is 5.5 kg.

The sensing device used is the STS-5 gas counter, which is located in the head of the probe. It consists of a steel cylinder (cathode) with a thin metal filament, the anode, stretched along its axis. The space inside the counter is filled with a single atom gas (argon) with multiatom gas (halogens). A high voltage (400 v) is applied to the electrodes from a high voltage generator. As distinct from the ionization chamber, the counter operates under conditions of gas amplification; if a gamma-ray quantum or beta particle passes through the counter and forms at least one pair of ins, an electric discharge occurs in it, as a result of which a voltage is created in the anode circuit at the load resistance. The discharge lasts for about 10^{-4} seconds, and after it has ceased the counter is ready to record the next particle. The number of voltage pulses in the circuit per minute is proportional to the radiation intensity and the degree of
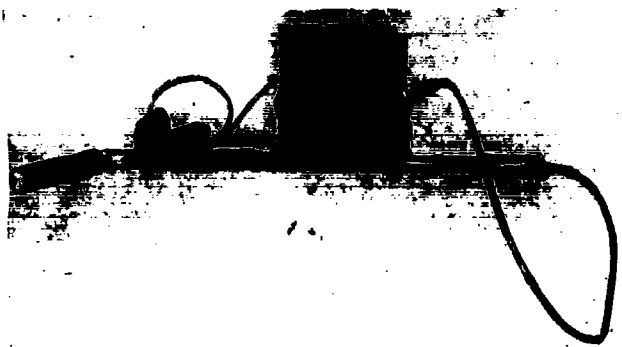
-320-

Fig. 98. External view of field r-meter.

contamination of the surface above which the counter is placed, accordingly. As soon as the pulses are amplified, they are turned into direct current, the strength of which is proportional to the number of particles recorded per minute. The current is measured by means of a microammeter with a scale shown on the control panel (Fig. 99). On the lid of the instrument there is a calibrated table which is used to convert the microammeter readings into decays/min cm^2 (scale B_1 or B_2 of the table), and into milliroentgen/hour (scale Γ) when measuring gamma radiation.
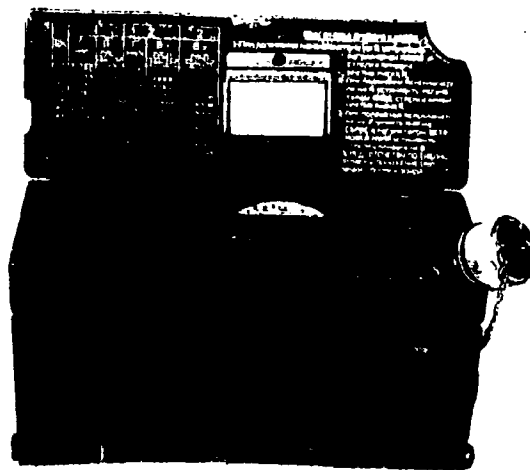

Fig. 99. Control panel of field r-meter.

The sound consists of a head and a stem. The head is joined to the stem by a swivel hinge and may be set in two positions: straight (when the stem and head are in a straight line) and an angular position (as shown in Fig. 98). The head contains a holder for securing the counter, an airtight covering with perforations covered over with thin aluminum foil, and a swivelling casing made of aluminum 4.6 mm thick. The latter can be twisted and fixed in different positions marked on the head of the probe (Fig. 100).

When measuring a weak contamination, the casing is twisted into position B_1 (in this case violet tinted foil is visible through the perforations). When measuring relatively strong beta contamination, the head of the probe is set in position B_1. In this case the beta particles can only enter the counter unimpeded through one narrow perforation.

For gamma radiation the casing is twisted into position Γ. Here the counter is enclosed by a aluminum shield 4.6 mm thick. This shield totally absorbs the beta particles while virtually not affecting the gamma radiation.

Fig. 101 shows a simplified circuit for this instrument. It consists of a gas counter, a high voltage generator to power the counter, a amplifier-restricter, and a device to measure the frequency of   the   volt meter pulses.
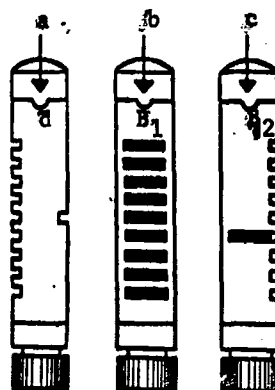
Fig. 100. Head of probe: a) for measuring gamma radiation; b) for measuring weak beta contamination; c) strong beta contamination.

The voltage pulses picked up from the load resistance in the counter circuit

/R$_V$ pass through the separating condenser C and reach the grid of the tube L$_1$, which is the amplifier-limiter. The anode circuit of this tube contains the earphones and the first winding of the transformer T. When the pulses have been amplified and limited in amplitude, they are fed to the diode section of the tube L$_2$. The diode circuit contains an averaging circuit C$_0$R$_0$, the aim of which is to produce a direct voltage proportional to the frequency at which the pulses follow each other. From the averaging circuit the voltage passes to an electronic voltmeter with an amplifying tube (right-hand side of the tube L$_2$), the anode circuit of which contains the microammeter A. If the instrument is calibrated, the variation in the anode current of the tube tells us the number of pulses created by the counter per unit time, and thereby the degree of contamination of the surface being examined.

The averaging circuit consists of the resistance R$_0$ and the condenser C$_0$ connected in parallel. The counter does not discharge at equal intervals, but, rather at any time at all (in accordance with the statistical nature of radioactive decay). Hence, the arbitrary piling up of voltage signals in the averaging circuit makes them vary about a mean value. The variation (fluctuation) is indicated by the microammeter needle, and the less the number of signals per unit time and the less the time constant of the circuit, the greater the fluctuation. Large fluctuation is impermissible since it makes it difficult to take the reading. But if it is not possible to increase the time constant excessively, since it determines the set-up time for the readings, which is one minute in the case of the first range, and 0.5 minutes for the second range. This difference is due to the fact that high intensity radiation is measured with the second range, so the number of pulses created by the source is greater and the time constant may be less at the same fluctuation of the needle. The variation in the time constants is attained by varying the resistance R$_0$ and the capicitor C$_0$ of the averaging circuit when switching one sub-range to another.
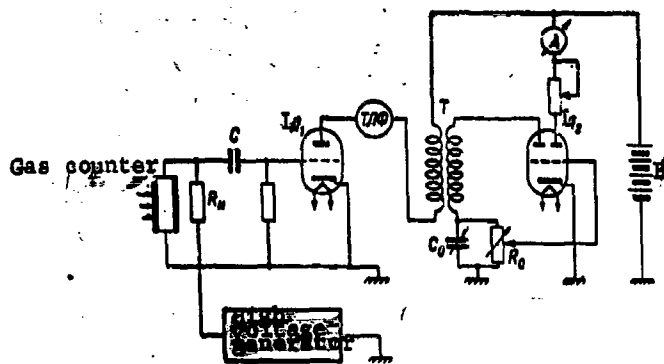
-323-

Fig. 101. Simplified circuit for field r-meter.

In order to prepare the instrument for measurements the following is necessary:

1) The control panel is slung at waist level by means of straps so that the readings can be conveniently taken.

2) The probe and earphones have to be connected to the control panel (at nighttime the illumination for the scale is switched on).

3) The power system has to be checked at 0 (instructions for checking the instrument are given on the lids).

Whether or not the instrument is working correctly is indicated by the buzz in the earphones from the high voltage generator and the clicking sound heard at intervals due to the effect of natural radioactive radiation and cosmic particles (when there is no radiation, the needle should not be deflected more than 8 to 10 divisions on the first sub-range). In order to check the working order more thoroughly, use can be made of a control preparation which is part of the kit.

When making measurements, the probe is held in the hand and the head of it is brought within 1 - 1-1/2 cm of the contaminated surface. The head of the probe should not touch the contaminated surface since it may become contaminated with radioactive material.

As has already been mentioned, the instrument has a relatively high set-up time, which may lead to a large amount of wasted time during the actual monitoring.

-324-

time. In order to speed up operations it is advisable to use the headphones. These record separate voltages in the form of clicks which are detected by the ear virtually without any time lag. The use of the phones makes it possible to detect spots with a relatively high degree of contamination very quickly, and this speeds up the monitoring of objects with a large surface (tanks or aircraft).

Measurment of the degree of contamination can be carried out fairly frequently if there is considerable gamma background. This background may be created by gamma radiation emitted from areas a long way away from the region of the surface close to which the counter is placed. For example, a monitor inside an aircraft may be affected by gamma radiation emitted by radioactive material on the wings, tail unit and so on. On account of the great penetrating power of gamma radiation, it is not possible to prevent it having an effect on the counter. Hence the degree of contamination is determined by means of two measurements:

1) by measurement of the total beta particle flux and gamma ray quanta (casing turned into position B_1 or B_2);

2) by measurement of only one gamma-ray quantum flux (casing turned into position Γ).

The difference between the first and second measurements shows the degree of contamination of the surface.

If the gamma background is low (0.1 of the total beta or gamma radiation), only the first measurement need be taken.

As already pointed out, it is impossible to use the r-meter within a contaminated area of open terrain on account of its high sensitivity. In such cases radiometric measurement NECESSITATES TAKING SAMPLES OR/ using protective properties of field installations (dugouts, huts). When making beta measurements inside installations, the background created inside by the contaminated terrain must be taken into account as well.

Food products as well can be tested for contamination either by directly

--325-

measuring the degree of contamination of the surface of the products, or else by taking samples. Results of the measurements of a sample of a certain weight shows the degree of contamination per gram of given product. Water may be tested by immersing the height of the probe. In this case a thin rubber covering is placed over the head to prevent it from being contaminated by radioactive materials in the water. The results give the degree of contamination per liter of water.

The monitor may be calibrated from a standard point source of gamma radiation (C_s^{60}) or by a standard beta radiation source, which is plate of a fixed size with different degrees of contamination.

Gamma ray calibration is carried out in the same sequence as for the r-meter. It has been found that a monitor graduated for gamma radiation provides a satisfactory degree of accuracy in meauring beta contamination.

5. Decontamination

The removal of radioactive material from the integuments and mucous membranes of the eyes, nose and mouth of humans and animals, and the removal of radioactive material from equipment, vehicles, weapons and defense installations, from terrain as well as water, food and fodder is known as decontamination.

Decontamination is only carried out, on the whole, if the contamination excedds the norm. If it is not possible to determine the true degree of contamination for any particular reason, decontamination is carried out as a prophylactic measure. In all cases the decontamination is carried out in such a way that it does not interfere with the normal combat missions.

Decontamination is either partial or complete, according to the military situation.

Partial decontamination is carried out at the first opportunity, directly in the field.

Complete decontamination is only carried out in a non-contaminated area at the orders of senior commanders at prearranged decontamination points (PDP). A rough layout of a decontamination point and the sequence in which personnel pass

through it are shown in Fig. 102. The point consists of the following units:

    a) monitoring-distribution point;

    b) area for decontamination of weapons, equipment and vehicles;

    c) area for decontaminating uniforms and personal equipment;

     PERSONAL
    d) decontamination area;

    e) area for decontaminating animals, if necessary.

Troops required to go through complete decontamination are concentrated in the waiting area, where they undergo partial decontamination, if this has not already been done.
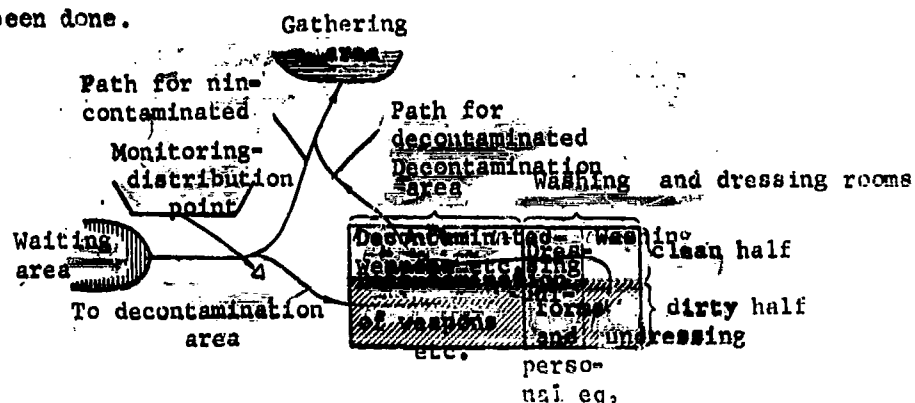

Fig. 102. Layout of decontamination point.

The personnel pass from the waiting area to the monitoring-distribution point. There they are monitored for contamination. If the degree of contamination is higher than the norm, they are sent to A / *SPECIAL* decontamination *AREA* together with weapons and equipment - the / *UNPROCESSED* half of the area for decontaminating weapons, equipment and vehicles. Here they put on special protective clothing and decontaminate their weapons and equipment, after which the latter is transferred to the clean half of the same area, while the personnel proceed to the uniform and personal equipment decontamination area. The soldiers leave their uniform and personal equipment for decontamination on the dirty half of this area, and then proceed to the *PERSONAL* decontamination area. In certain cases after their weapons and equipment have been decontaminated, they move on to the undressing section of the *PERSONAL* decontamination area. In the undressing section they take off their special protective clothing and

-327-

leave their uniform, personal equipment, underwear and footwear for decontamination. All these operations are carried out by specially assigned teams. After decontamination the clothing, etc., is transferred to the dressing section.

After personal decontamination, the soldiers proceed to the clean half of the area for decontaminating arms, equipment and vehicles, where they clean and lubricate the weapons and equipment and then move onto the assembly region.

The decontamination point is carefully sheltered from aerial observation and as far as possible is close to a source of uncontaminated water. The site of the decontamination point should be level with a slight incline to drain away water. The drains should be dug in such a way that the contaminated water flows away from the source and collects in a reservoir or water-absorbing well.

The large numberof operations involved in complete decontamination requires the use of special machinery and apparatus, the majority of which is also used for decontamination from gas and disinfection. The washing truck is intended for decontamination of vehicles and may be used to decontaminate sections of highways (with a hard covering), bridges, installations and so on. The truck reservoir has a capacity of 2650 liters. The liquid can be fed mechanically or by a hand pump. The automatic decontamination truck is used to decontaminate military equipment and vehicles. The gas-decontamination haversack is used for the same purpose.

Artillery and machine gun-mortar gas decontamination equipment is used for partial decontamination of guns, mortars and machine guns. To decontaminate personnel and uniforms, use is made of a pray unit.

Decontamination of personnel. Partial decontamination of personnel is organized in the field at the first opportunity without the withdrawal of troops from combat duties. It may be carried out directly in the contaminated area or after the area has been left.

During partial decontamination outside the contaminated area, the first thing to do is remove the protective caps and shake any dust from the uniform, and then to take off the protective gaiters.

The gas mask and protective gloves should then be taken off, after which the hands should be washed and the exposed parts of the body should be swabbed two or three times with uncontaminated water, making certain the process is thorough and that all dirt is removed from underneath the fingernails; the nose should then be cleaned with clean water and the mouth rinsed.

If there is not sufficient water, the exposed parts of the body are wrapped with damp towels; handkerchiefs or some other damp cloth can be used. If there is no water at all, the swabs are soaked with liquid from the individual anti-gas packet. If the worst comes to the worst, and neither the packet nor water are available, the exposed parts of the body can be rubbed with dry swabs.

It is not possible to take off protective clothing during partial decontamination in a contaminated area. Radioactive material can only be removed from the unprotected areas of the body. Water can only be used for this purpose when the source of it has been monitored at the commanding officer's orders. If the troops are in a contaminated area without any protection, the exposed parts of the body should be washed or rubbed, after which the protective clothing should be put on and weapons and the fortifications should be decontaminated. When the weapons, fortifications and equipment have been decontaminated, the exposed parts of the body should be washed or rubbed with moist swabs once again in order to remove any radioactive matter which might have got onto the skin during decontamination.

Complete decontamination is only carried out in an uncontaminated region in a special area. In populated points baths, showers and disinfection huts, should be used. In the field, in summertime, disinfection can be carried out in the open air, in tents or under awnings, or in a non-contaminated reservoir with running water, and in cold weather warm huts or heated tents are set up. In complete decontamination the whole of the body is carefully washed. Monitoring is carried out before and after washing.

Washing contaminated places with warm water and soap, using a mop, ensures

complete removal of radioactive material and is one of the most effective, and at the same time accessible, methods of decontamination.

Experiments with different types and methods of dealing with the hands has shown that when first washed with a scrubbing brush and soap most of the radioactive material is removed, and that consideably less is removed during the second washing. Washing the hands a third time with soap and water, using a soft brush, removes practically all the radioactive material. The use of solvents, weak solutions of hydrochloric acid and potassium permanganate solutions produces much the same results as washing with a brush and soap.

Decontamination of equipment and arms. Partial decontamination of equipment and weapons, just as partial decontamination of personnel, may be carried out in the actual contaminated zone or after it has been left.

For partial decontamination of weapons and equipment the soldiers prepare several swabs made of uncontaminated cloth or rag, and having wet them with water (or if there is no water, with paraffin, gasoline or some other solvent), carefully wipe their own rifles or submachine guns and the parts of the vehicle, artillery, tank or aircraft which hey constantly come into contact with, that is to say, seats, handles and so on.

If the military situation makes it possible, the radioactive material should be removed from all surfaces of contaminated firearms (rifles, submachine guns, machine guns), artillery guns, mortars and so on. This reduces the overall contamination of the armaments and equipment to a considerable degree, and reduces the possibility of injury when using them.

Partial decontamination of small arms, field guns and mortars is carried out at the actual gun emplacements. During decontamination particular attention must be given to optical instruments (stereotelescopes, sites, range finders and so on), since if contaminated optical instruments are used, they may damage the organs of sight. If there is no water, gasoline or paraffin available, the weapons and equipment should be wiped three or four times with clean, dry rags.

Tanks and self-propelled artillery guns are decontaminated by their crews. For partial decontamination the crew first wipes clean the places on the tower and body of the tank with which they come into contact. Then they decontaminate the inside, the controls and the armaments, equipment, instruments and levers.

Fig. 103 shows by means of arrows the parts of an aircraft which are the first to be decontaminated. These include the cabin lights, cabin entrance and some of the hatches, the inside surface of the cabins and their equipment, if they prove to be contaminated when monitored.
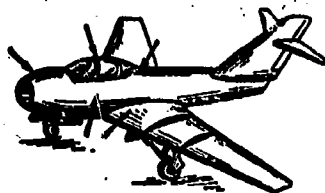

Fig. 103. Parts of an aircraft which are first to be decontaminated.

Complete decontamination of arms and equipment is only carried out in a non-contamined region in specially prepared areas. The operation is carried out under the guidance of specially trained personnel.

Weapons and equipment are decontaminated by one of the following methods: by washing off the radioactive material with a stream of water; by washing off the radioactive material with water rubbing the surface at the same time with brushes or rags; by scrubbing with brushes, or swabs dipped in water; by washing with gasoline or paraffin. In wintertime non-freezing water solutions or gasoline and paraffin are used for decontamination. Gas decontamination solutions can be used with good effect.

Decontamination from radioactive material can be carried out with different gas-decontamination machinery and devices as well as gasoline, water and oil fillers, motor pumps, fire engines and other equipment. Fig. 104 shows complete decontamination of weapons and equipment; guns, tanks and aircraft.

-331-

Just before tanks are completely decontaminated, the ammunition and tools are taken out; the cover over the tower and driver's hatches are covered, the emergency exit and the hatchways in the bottom of the tank are opened, and louvers and other openings are covered with tarpolin. Exactly the same operation is carried out in the case of complete decontamination of aircraft: cabin lights, bomb doors and other openings are covered over. The decontamination is carried out from tp to bottom to make certain the contaminated water flows away.
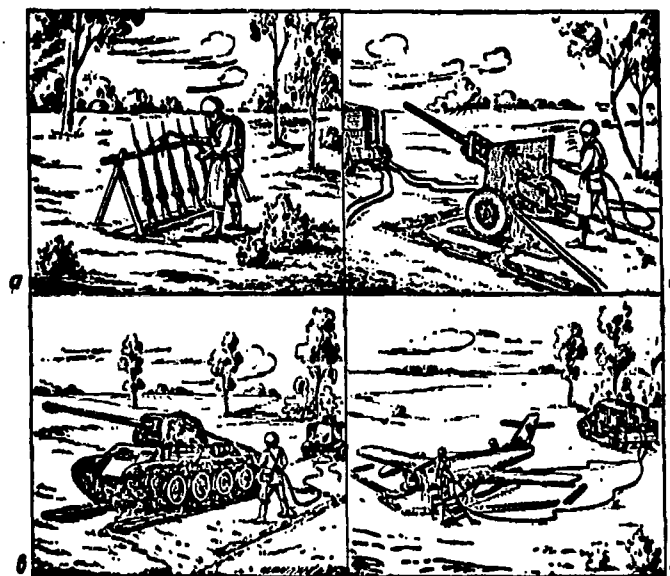

Fig. 104. Complete decontamination of weapons and equipment: a) complete decontamination of weapons using a haversack-type gas-decontamination device; b) complete decontamination of field guns using a gas-decontamination truck; c) complete decontamination of a tank using a water-carrying truck; d) complete decontamination of an aircraft using a gas-decontamination truck.

In all cases the most advantageous method of washing down equipment, particularly when it is large in size, from the point of view of saving time and toil, is to use a hose pipe. In certain cases, however, it is more effective to wash down with water, scrubbing the surfaces at the same time. This method is more laborious, but on the other hand, removes radioactive material more effectively with comparatively small consumptions of water.

The inside of aircraft, tanks and trucks can be decontaminated with vacuum cleaners.

The principal methods of removing radioactive contamination aboard ship is to wash down decks, superstructures, towers and other installations with a jet of high pressure water. Fire hoses and special pipes with sprays give the best results. By means of powerful pumps water from the sea is fed to the pipe and then forced through a large number of fine holes forming a sort of char which successfully washes the radioactive material from the outside of the ship.

After this treatment all the decontaminated objects should be carefully monitored. If it is discovered that in places there is more radioactive material left than the norm, the decontamination is carried out a second time with subsequent remonitoring.

Decontamination of uniform and personal equipment. Partial decontamination of uniform, personal equipment and protective clothing is carried out by the personnel in battle formation and usually after partial decontamination of weapons and munitions. Outside the contaminated area partial decontamination of these items is achieved by brushing and shaking out the radioactive dust.

If there is enough time and the situation is suitable, personal equipment and uniform is taken off, carefully shaken, brushed and rubbed. In winter these items can be decontaminated with clean snow.

If a cape has been worn over the uniform, the only parts of the uniform and equipment shaken and brushed are those which were not covered.

Complete decontamination of uniforms and personal equipment and also protective clothing is carried out at the decontamination points. The following methods are used to remove radioactive material: shaking and beating; rubbing with swabs or brushes, washing and laundering.

After decontamination, the uniform is monitored and then returned to the personnel. If it is found that the degree of contamination is still high, the uniform is replaced.

<u>Decontamination of food and water</u>. All types of food and fodder contaminated above the norm must be decontaminated or taken away. Stocks of food carried about are destroyed if they become contaminated. The exception is canned food and other products in airtight containers. These products can be used when the packing material has been decontaminated.

Water is only decontaminated when there is no other source available, that is to say when there is no chance of digging a new well, drilling a hole or sending for water from an uncontaminated region.

After an atomic attack all food products, fodder and water supplies in the area of destruction are monitored in order to establish the degree to which they are contaminated. Selection of the decontamination method depends on the nature of the products (whether bread, meat, sugar, canned goods and so on), on the type of packing, on the degree of contamination and on the availability of different technical means of decontamination. Given the large variety of food products, it is difficult to recommend any one method for decontamination.

Food products and fodder kept in sacks (buckwheat, salt, grain and so on) are transferred to clean sacks or some other clean packing material, observing the necessary precautions.

The decontamination of fish, fats, corned beaf kept in barrels or crates is carriedout by washing them with water and rubbing them with rags or scrubbing.

Decontaminated food products and fodder are kept separately and used last. When they are issued from the storehouse, special entries are made in the relevant documents. Such food products are washed more carefully before being put in the saucepan.

Contaminated water may be decontaminated in different ways. Most of the radioactive material formed by an atomic explosion does not dissolve in water, hence as time passes it settles on the bottom of the reservoir. The process of precipitation, however, goes on very slowly and, as a rule, there is no complete filtering; hence the main ways of decontaminating water are to filter it or distil it.
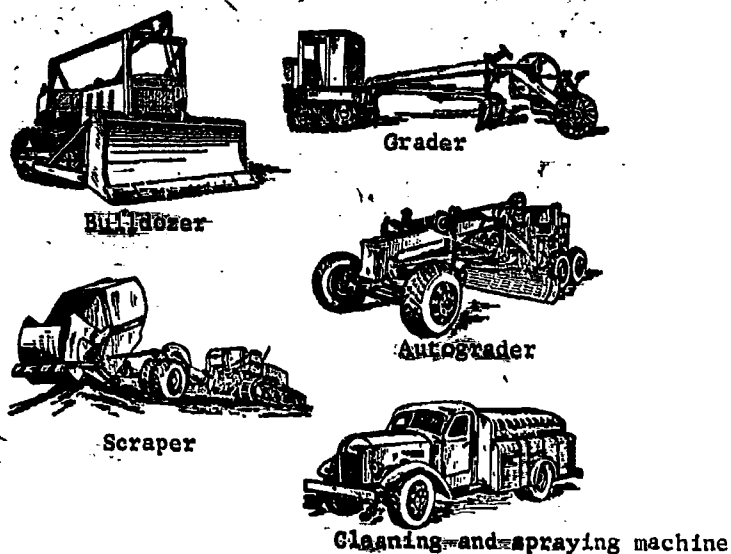
Fig. 105. Machines which can be used to decontaminate roads and areas of a locality.

The successful advance of troops throughout the battle is furthered to a considerable extent by the ability to cope with contaminated areas which may be encountered both in the vicinity of the explosion as well as in the wake of the radioactive cloud.

Contaminated areas can be quickly dealt with in protective clothing (Fig. 106). When moving up in calm, still weather after rain, there is no need to wear gas masks since there will be very little dust, and therefore very little radioactive matter in the air. In this case only a ground sheet or protective cape need be put on. When crossing contaminated terrain, protective clothing should be used in accordance with the military situation and the weather, and attention should be given to the soil and vegetation since they affect the degree of dust formation.

In dry weather, gas masks and protective gloves should be put on when crossing contaminated areas. In damp weather the gas mask need not be used, since there is hardly any radioactive dust in the air. But protective gaiters, gloves and various

-337-

Distillation by means of mobile stills is carried out in the same way as the distillation of salt water. Water can be filtered through issue filters or filters improvised with local materials (sand, gravel, coal); the filtration may be preceded by coagulation and stagnation. Coagulation is a method of purifying water by means of artificially producing a sediment by adding special chemicals to the water (coagulants). The method ensures the removal of very fine particles suspended in the water.

The method of ion exchange can be used for filtration, since it ensures better removal of radioactive removal from the water, that is to say both insoluble and soluble material. In this case, apart from the normal filtering materials (gravel or sand), the filter contains special substances called ionites. Ionites are granular solids, insoluble in water, which possess the power of absorbing ions from solutions.

When decontaminating wells and springs which have become contaminated by radioactive material, the bottom of the well is cleaned and the water pumped out of it several times. In the case of springs, a layer of soil 5 to 10 cm thick is removed. The degree of contamination of the water and the walls of the well is checked before and after decontamination.

Decontamination of positions and terrain. Trenches and communicating passageways with lined walls are decontaminated in the following order. Three to four cm of soil are removed from the berm, after which the lined walls are brushed with moist brooms, grass or straw braids, brushes or rags. The soil removed is put shoveled into buckets, boxes or sacks and taken to a spot indicated by the commanding officer. The bottom of the trench is then decontaminated by removing a layer of soil 3 cm thick. Soil can only be removed from the rampart if the camouflage makes it possible.

Unlined trench walls are cleaned with shovels by the removal of a layer of soil 3 cm thick.

Buildings and closed installations are decontaminated by wiping the ceilings, floors and walls with damp rags, or else they are swept with damp brooms or scrubbed.

The decontamination of terrain involves the removal of radioactive material from the surface or covering the surface with a layer of uncontaminated material. Both methods are very cumbersome and laborious, hence only certain areas of the locality are decontaminated, mainly paths and points where military equipment and personnel are located. Street cleaning machines (Fig. 105) of different kinds are usually used for this purpose.

When determining the extent of the decontamination of the locality, it is advisable to have as much accurate reconnaisance data as possible on the size of the contaminated area and the radiation level in it, particularly where troops are located or points through which routes pass.

When organizing decontamination operations, inasmuch as the situation allows, so-called self-decontamination should be employed; self-decontamination is a reduction in the degree of contamination as a result of the spontaneous decay of radioactive material.

As has already been mentioned, the greatest protection from radioactive material during operations in a contaminated locality is to cut down the time spent by troops in that locality and to prevent radioactive material getting onto the skin or into the body.

Present-day engineering enables us to cope with contaminated areas fairly swiftly, thereby ensuring the   FIRST   of the above-mentioned conditions; the second condition can be reliably satisfied by the use of personal precaution. Thus, if necessary, hostilities are quite possible on contaminated terrain without the application of decontamination methods.

6. Operations in a contaminated locality

In a situation in which atomic weapons are used, a high degree of training, endurance, courage, iron discipline and the will to victory will be required far more than ever before. In order to carry out his combat duties successfully, every soldier must be able to operate ably, showing initiative and skill in battle.

Fig. 106. Crossing contaminated terrain. When crossing co..taminated terrain
the protective cape should be spread out as an underlay.

underlays should be used in this case to protect the clothing and footwear from

contamination when lying on the ground. Fig. 107 shows the passage through
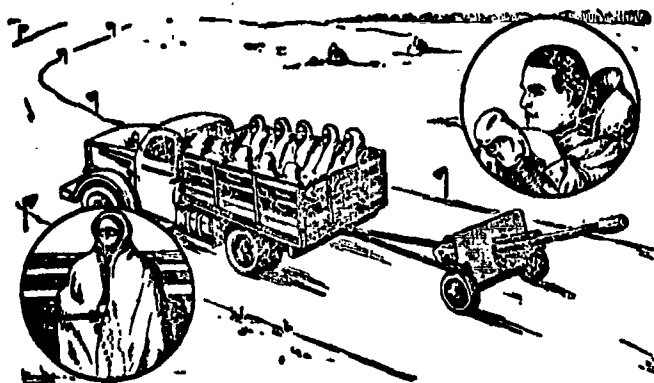
contaminated areas in a truck.

Fog. 107. Passage through a contaminated area in a truck. The insets show the
use of protective clothing.

Instructions on the use of different protective measures are usually issued

by a senior commanding officer. If the troops are operating in contaminated terrain

same way from other troops, the decision to use protective clothing is taken in-
dependently by the commanding officer.

During operations involving the use of atomic weapons, soldiers should
attend constantly to their own weapons and equipment, personal food supplies and
water, ensuring their protection from contamination by radioactive material.

One of the ways of ensuring protection against injury by irradiation is
to limit the amount of time spent in a contaminated area. If the period is com-
paratively short, as when crossing contaminated areas, the variations in the
radiation level with time can be ignored and the radiation dose can be determined
from a very simple equation, namely

$$D = P_m \cdot t,$$

where $\underline{D}$ is the radiation dose in roentgens;

$\underline{P}_m$ is the mean radiation level over the given area in roentgen/hour;

$\underline{t}$ is the time in hours.

The period which can be safely spent in a contaminated area, taking the
variation in radiation level into account, can easily be determined by means of
graphs. If the time of measurement of the radiation level and the time of entry
into the contaminated region coincide, to determine the amount of time which may be
spent we can use the graph in Fig. 108. The vertical axis plots the ratio of the
total irradiation dose to the radiation level observed when entering the region,
and the horizontal axis shows the time of entry, counted from the moment of the
explosion. Each curve corresponds to a definite period of irradiation.

Example. Let us suppose that a team has arrived in a contaminated area
10 hours after the explosion. The measured radiation level is 10 roentgen/hour.
We are required to determine the safe period, if the given allowed dose is 25
roentgens.

Solution. Since $D/\underline{P} = 25/10 = 2.5$, $\underline{t} = 3$ hours. The solution is shown
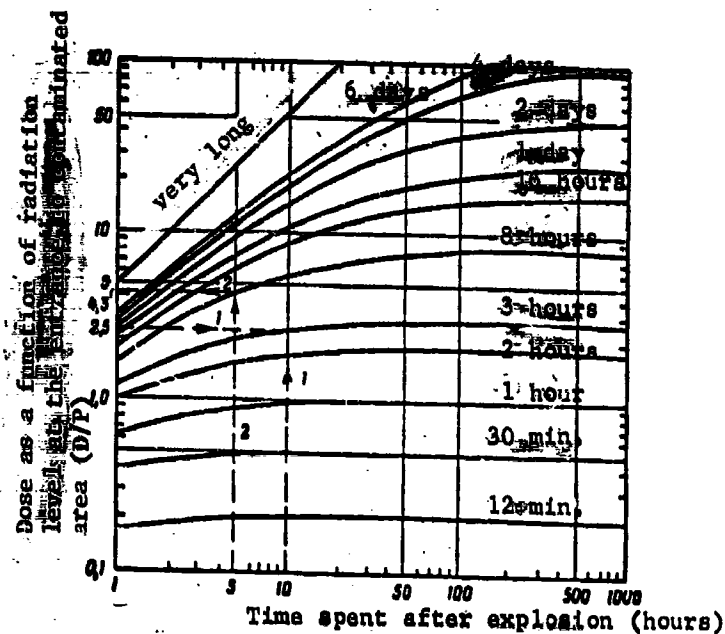by arrows 1 - 1 in the graph.

Fig. 108. Graph for determining time which can be safely spent in contaminated area (duration of irradiation shown on curve).

A slightly different problem can be solved. Suppose, for example, we are required to determine the dose which can be obtained by staying 8 hours in a contaminated area if the team arrives 5 hours after the explosion when the radiation level is 10 roentgens/hour.
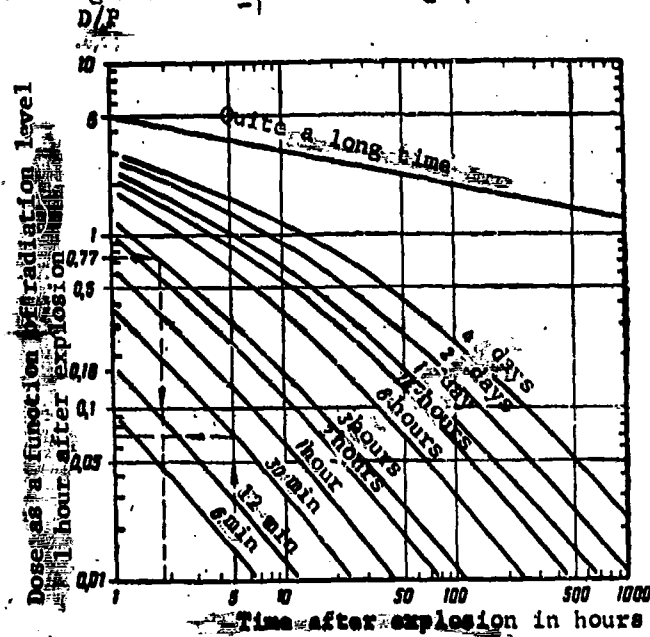
Solution. Using the graph we find that $D/P = 4.3$. Hence $D = 4.3 \cdot 10 = 43$ roentgens. This solution is shown by the arrows 2 - 2.

In a similar graph (Fig. 109), the vertical axis plots the ratio between the dose and radiation level observed one hour after the explosion. In this case to determine the time troops are allowed to stay in the area we have to know the radiation level an hour after the explosion. There may be cases, however, when the radiation level is determined, let us say, three hours after the explosion, although the troops began operations in the area 2 or 5 hours afterwards. Hence we have to use another graph (Fig. 110), which shows us the radiation level an hour later (P_1) from the measured irradiation level.

Examples. 1. Thirty minutes after the explosion the radiation level $P = 60$ roentgen/hour. The allowed dose $D_{all} = 20$ roentgens. Three hours are required

-340-

to carry out operations. How long do the troops have to wait before beginning work in the area?

Solution. The graph in Fig. 110 shows us the radiation level an hour after the explosion. To find it we draw a vertical line from the point representing a radiation level of 60 roentgens/hour on the horizontal axis up to the point where it intersects with the straight line showing a post-explosion time of 30 minutes. Then we draw a horizontal line to the left and read off the radiation level on the vertical axis. In the given case $P_1 = 26$ roentgen/hour.

Fig. 109. Graph for determining safe period in a contaminated region on the basis of the radiation level an hour after the explosion (the irradiation time is shown on the curves).

Let us now go on to look at the graph in Fig. 109. The ratio between the allowed dose and the radiation level an hour after the explosion is

$$\frac{D_{all}}{P_1} = \frac{20}{26} = 0.77.$$

We draw a horizontal line from the point corresponding to 0.77 on the vertical axis to the point of intersection with the curve, which shows a period in

-341-

the contaminated area of 3 hours. From this point we draw a line downwards and on the horizontal axis find the time which has passed since the explosion. In the particular problem under consideration we find $t \approx 2.0$ hours.
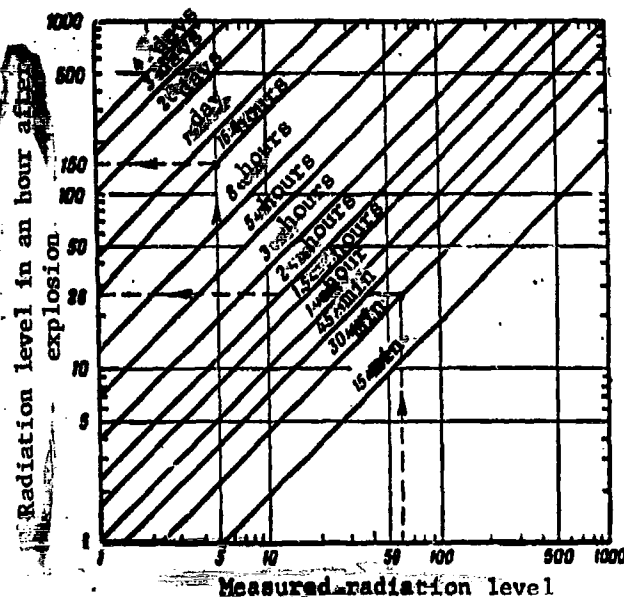

Fig. 110. Graph for determining radiation level one hour after explosion (straight lines show amount of time passing since explosion up to moment of measuring radiation level).

2. We are to determine the total dose received by a person who entered the contaminated area five hours after the explosion and remained 30 minutes in it. Measurements made 16 hours after the explosion show that the radiation level is 5 roentgen/hour.

Solution. The graph in Fig. 110 shows us that an hour after the explosion the radiation level is

$$P_1 = 150 \text{ roentgen/hour}$$

Using the graph in Fig. 109 we find the ratio D/P_1, which proves to be 0.07, consequently,

$$D = 0.07 \cdot 150 = 10.5 \text{ roentgens}$$

If conditions allow, troops, armaments and equipment should be monitored after passage through a contaminated locality, and partial decontamination should be carried out after the monitoring.

CONCLUSIONS

The Soviet Government's declaration points out that never before has the arms race been fraught with such dangers as today, in the age of the atom, electronics and the conquest of space. However terrible rapid-firing automatic weapons, tanks, long-range artillery and bombs may have seemed as methods of exterminating human beings, they cannot BEAR comparison with atomic and hydrogen weapons and rockets. If we put together all the means of destruction which mankind has possessed throughout the centuries, they would only make up a tiny part of what is now in the hands of two or three powers possessing nuclear weapons.

After all, it is well known that the explosion of only one contemporary hydrogen bomb releases destructive energy greater than the energy of all the explosives made throughout the world during the four years of World War II.

The explosion of one such bomb could wipe the largest centers of world civilization from the face of the earth. Just a few hydrogen bombs are required to eliminate whole states. Yet more and more atomic and hydrogen bombs are being accumulated.

The adoption of nuclear and rocket weapons by armies, the training of the armed forces in handling them, the adaption of strategy and tactics to the new types of weapons in war have now reached such a pitch that the next

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The Soviet Government's declaration on general and complete disarmament ("Pravda" for September 19, 1959) states that all the atomic and hydrogen bombs in the possession of states in the present time should be destroyed and that further production of them should be halted. The energy from fissionable material should be used exclusively for peaceful, economic and scientific purposes. The production of all types of rockets of all ranges should be ceased and they should be liquidated, including space rockets intended for military purposes. Rockets of all ranges should be destroyed and rocketry should remain merely as a means of transportation and a means of conquering space for the good of mankind.

military conflict between powers could easily turn into a war with the use of all these methods of . . . . annihilation in the possession of the belligerent parties. Outer space, which only a few years ago was inaccessible to man, can now be used, as the sea and air were earlier for striking any point on the globe with nuclear attacks.

It is pointed out in the foreign military press that the development of nuclear weapons over the last 15 years has been very rapid and has had a strong effect on methods of armed combat. Atomic weapons make it possible first and foremost, to greatly increase the striking power of artillery and aviation. This makes it possible to speed up and intensity military operations to incredible extents and to increase the role played by surprise. The adoption of long-range rockets with nuclear warheads makes it possible to destroy the enemy's defense lines as well as his tactical and operational rear from distance launching sites, and, furthermore, very rapidly and effectively by maneuvering the trajectories. Nuclear weapons have begun to take a place in anti-aircraft defense, chiefly in the form of guided anti-aircraft missiles. Reports have appeared in the foreign press on the use of nuclear warheads in guided aviation missiles intended for aerial combat.

The foreign press points out that warships and submarines are also being equipped with guided and homing rockets and torpedoes with nuclear warheads. This has radically changed the naval tactics and has greatly improved its striking power both in action against other ships as well as coastal territory and enemy bases.

Engineering units have been considerably strengthened since they now have the chance of carrying out rapid demolition work with nuclear charges in order to erect barriers, and for other purposes.

According to foreign experts, strategic air forces and other types of strategic weapons, particularly long-range and intercontinental rockets, and nuclear warheads have made it possible to greatly increase the strength of

strategic aircraft as well as other types of strategic weapons, particularly long-range and intercontinental rockets. This now makes it possible to strike deep and hard at the heart of the enemy, and much more effectively than any of the attacks by strategic aircraft which could have been made in the recent past. Hence at the present time it is possible to wage a war in which there is no great difference between the front and the rear, and in which cities, transportation and industrial centers pinpointed on the map can be hit more easily, more swiftly and more effectively than troops that have been duly dispersed, camouflaged and sheltered. All this changes the face of modern warfare, military preparedness and organization of the armed forces.

Particularly important is the nuclear warhead carrier - the Soviet intercontinental rocket - which can hit targets in any given region throughout the world with suitable accuracy. This means of warfare considerably improves the defense capacity of the Soviet Union.

In his report at the session of the USSR Supreme Soviet on January 14, 1960, N. S. Krushchov said that "We are several years ahead of certain other countries in the construction and mass production of intercontinental missiles of different types."

"Our scientists, engineers and workers employed in the defense industry have constructed new types of armaments which are the very latest word in science and technology. This puts us in a position to reduce our armed forces without endangering the defense capacity of the country."

"The Soviet Union has piled a sufficient number of atomic and hydrogen weapons. Until we arrive at an agreement on the banning of nuclear weapons, we are forced to continue production of them. Naturally, we have to spend quite a lot of money for this purpose. But for the moment we cannot give up the production of atomic weapons: a decision of that nature must be the result of agreement between states possessing these weapons."

"Our State possesses powerful rocketry. At the present level of development of military equipment, military aircraft and naval units have lost their former significance. Weapons of this type are not being reduced, but rather replaced. Military aircraft have been almost totally replaced by rockets. We have already sharply cut down, and will obviously cut down further or even discontinue the production of bombers and other obsolete equipment. In the navy great importance is now assigned to the submarine fleet, for surface ships can no longer play the part for which they were designed in the past.

Our armed forces have been issued with rocket and nuclear weapons to a considerable extent. These weapons are being perfected and will continue to be improved until they are banned.

The Central Committee of the Communist Party and Soviet Government are in a position to tell you, Comrade Deputies, that weapons which we have are fearful weapons and those which, so to say, are in the offing are still more terrible. The weapons which are being designed and, as they say, are at the moment in the briefcases of scientists and designers, are incredible"[1])

The Communist Party and Soviet Government are steadily pursuing a policy of peace and friendship among peoples. The Soviet people is campaigning for the banning of atomic, hydrogen and other types of weapons of mass destruction. The imperialists continue to reject the USSR's peaceful proposals and are preparing for an aggressive war against the Soviet Union and countries of the socialist camp with the use of weapons of mass destruction. They are threatening us with the might of their air force and navy. "

"We can answer this by saying that these are relatively obsolete means of warfare; there is a much newer and more fearful means - intercontinental ballistic missiles. They cannot be stopped by any form of anti-aircraft defense, and they can land an atomic charge of collosal power at any point in the globe without fail (and indeed any point since they are very accurate). There need be no doubt about

this since the first rocket of this type shot up into outer space triumphantly and is now so proudly carrying out pement around the sun. What more proof do we need of the rocket power of the Soviet Union?!" [1]

At the present time the progress made by the Soviet Union in producing nuclear weapons and rocketry, and equipping the Soviet army, air force and navy with other types of modern armaments ensure reliable defense for our country against any aggressor. Our country is now equipped with different types of nuclear weapons, a whole series of ballistic missiles - intercontinental, long-range, medium-range and close-range continental missiles, and a whole group of technical rockets[2].

Out armed forces possess extremely good nuclear equipment which can strike both on the field of battle as well as anywhere else in the world.

In a speech at the session of the USSR Supreme Soviet on January 14, 1960, Marshall R. Ya. Malinovskiy pointed out that "Soviet armed forces are loyally guarding the Soviet people building the lustrous house of communism under the guidance of the Party. They are reliably and vigillantly protecting the interests of our country by remaining constantly in a state of complete battle readiness for resolute retaliation against an aggressor.

As regards technical equipment, military training and armaments, the Soviet Army and Navy has the advantage of the very latest attainments of science and engineering. They are equipped with the most modern and powerful means of warfare, the chief of which are rockets with nuclear warheads. In or armed forces

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1)
   R. Ya. Malinovskiy. Speech at XXI Party Congress: "Pravda" February 4, 1959.

2) Ibid.

these weapons are present in the form of ballistic missiles of different design, including operational-technical missiles with a range from tens to heveral hundreds of kilometers, and stragetic missiles, including intercontinental rockets with virtually unlimited range.

Present-day ballistic missiles with their tremendous velocity, altitude and range can drop nuclear warheads of different power anywhere at all in a very short time and in any weather. They make it possible to strike hard at a large number of objectives all at the same time. The long range and velocity of the missiles make it possible to maneuver them within a short time and thereby switch the main striking power from one theater of war to another, and change the situation to our favor by mass nuclear blows. It is not necessary to construct large, expensive and complex airfields to launch the rockets. The launching sites can easily be camouflaged and even hidden completely, ensuring their invulnerability.

All this shows that rockets are the most effective means of warfare existing earlier and existing now. Suffice it to say that if we suppose that over the years 1940- 1945 AngloAmerican airforces were able to drop about two million tons of bombs on objectives in Germany and the occupied countries by making a tremendous number of raids, at the present time one strategic rocket can hit the target with a nuclear warhead equivalent in power to the force of the conventional explosive contained in all these two million bombs.

If for purposes of clarification and analysis we look at the calculations made by our own and foreign experts, it has been shown that only about 100 such nuclear warheads need to be exploded over a short period of time over a State with developed industry and territory covering approximately 300 - 500 thousand square kilometers for all the industrial regions and administrative centers to be turned into a pile of ruins, and the territory to be made an arid desert with lethal radioactive contamination. Countries with large populations and a small

-348-

amount of territory are incredible vulnerable in this respect, while States with extensive territory, conversely, are highly invulnerable and much more likely to survive.

Rocket weapons with nuclear warheads are truly fearful weapons both in power as well as infallibility. Given the present state of means of warfare, it is possible to destroy a ship at sea or to shoot down a piloted or pilotless aircraft in the air without too much difficulty, it is for the moment impossible to destroy a rocket in flight once it has been launched; it inevitably hits the target.

In modern war, if it should be unleashed by the imperialists, prime importance is acquired by mass nuclear blows at objectives deep in the rear as well as at contingents of armed forces in the theater of hostilities.

We have taken this all into account and since we possess powerful modern weapons in the form of rockets with nuclear warheads, consider it quite possible to make considerable reductions in the Soviet armed forces without endangering our defense capacity...

The rocket troops in our armed forces are undoubtedly the principal arm of the services, but we realize that one such arm cannot solve all the tasks of a war. Thus, in view of the fact that hostilities in a modern war can only be conducted on the basis of coordinated use of all means of armed warfare and the joint effort of all branches of the services, we are retaining a certain number, in the relevant proportion, of all armed forces, which in action will bear little resemblance either in organization or in method of operation to what there was in the last war...

In determining the the further development of our armed forces in connection with their reduction, we proceed from the fact that the next war, should it be unleashed by the aggressors, will involve the mass use of atomic weapons. We stress this fact since many people in the West talk and write of a "restricted" nuclear war", "technical use of nuclear weapons", "Dose strategy", "intimidation

strategy", and so forth and so on. All these "theories" and "strategies" if they can be called such, testify to the fear on the part of the imperialists of inevitable retaliation which they may be subjected to if they attack the socialist camp. At the same time these "theories" are being preached to reassure the popular masses as a smokescreen to cover the dirty business of preparing for a new world war.

We should expect the most likely method of unleashing a war against the Soviet Union, if the imperialists risk doing so, to be a sudden attack with extensive use of atomic weapons. Under these circumstances the main task of our armed forces will be to rebuff the enemy attack and retaliate instantly with a crushing blow. This is what we are preparing our Soviet Army and Navy for first and foremost".[1]

Progress in economy, science and engineering has given us unquestionable advantage in ensuring the defense capacity of our country. We can rest assured that our scientists, engineers and technicians in the defense industry will continue to keep the upper hand in the field of nuclear weapons.

Academician I. V. Kurchatov has said that "Soviet atomic experts have been working hard for many years on instructions "from the Party and Government, first to create and then to perfect atomic and hydrogen weapons, full well realizing that the State is threatened and that if we do not have weapons of this kind there will appear forces striving to bring our wonderful Motherland to her knees. Soviet atomic scientists and engineers have done their duty to the country. They have created, perfected, economical and very powerful atomic and hydrogen weapons.

In addition to this, the Soviet designers of rockets and other carriers of nuclear weapons have done a brilliant job. Out citizens can rest assured - the defense of the Motherland is now looked after".[2]

In capitalist countries at the present time nuclear weapons and missiles intended to carry them are being rapidly developed and modified. The present state

of these weapons is only a transitional phase. Hence due knowledge of nuclear weapons and possibile methods of using them in war requires constant attention and study of new books, pamphlets and articles in journals and newspapers on this subject. At the same time there is need for a serious study of the physical and technical fundamental of nuclear weapons underlying their development. This book is indeed aimed at helping the readers to acquire this knowledge.

1)
  "Pravda", Jan. 15, 1960,

2)
  Ibid.

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